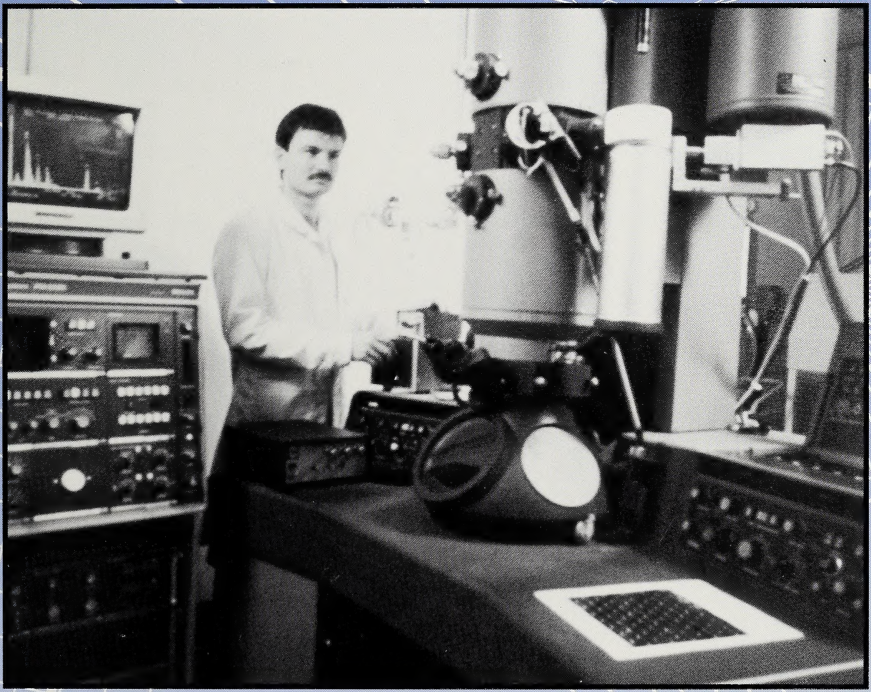
PHYSICS 30



Module 7

Quantum Theory

Distance Learning

Alberta EDUCATION

Physics 30

Module 7

Quantum Theory

Alberta
EDUCATION

Distance
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Student Module
Module 7
Quantum Theory
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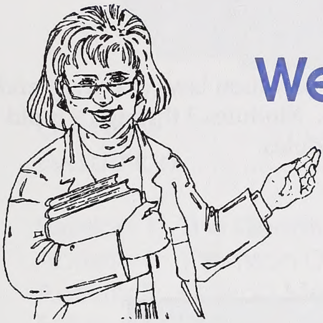
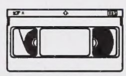


Welcome to Module 7!

We hope you'll enjoy your study of *Quantum Theory*.

To make your learning a bit easier, watch the referenced videocassettes whenever you see this icon.



You also have the option of viewing laser videodisc clips when you see the bar codes like this one.

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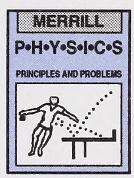
When you see this icon, study the appropriate pages in your textbook.

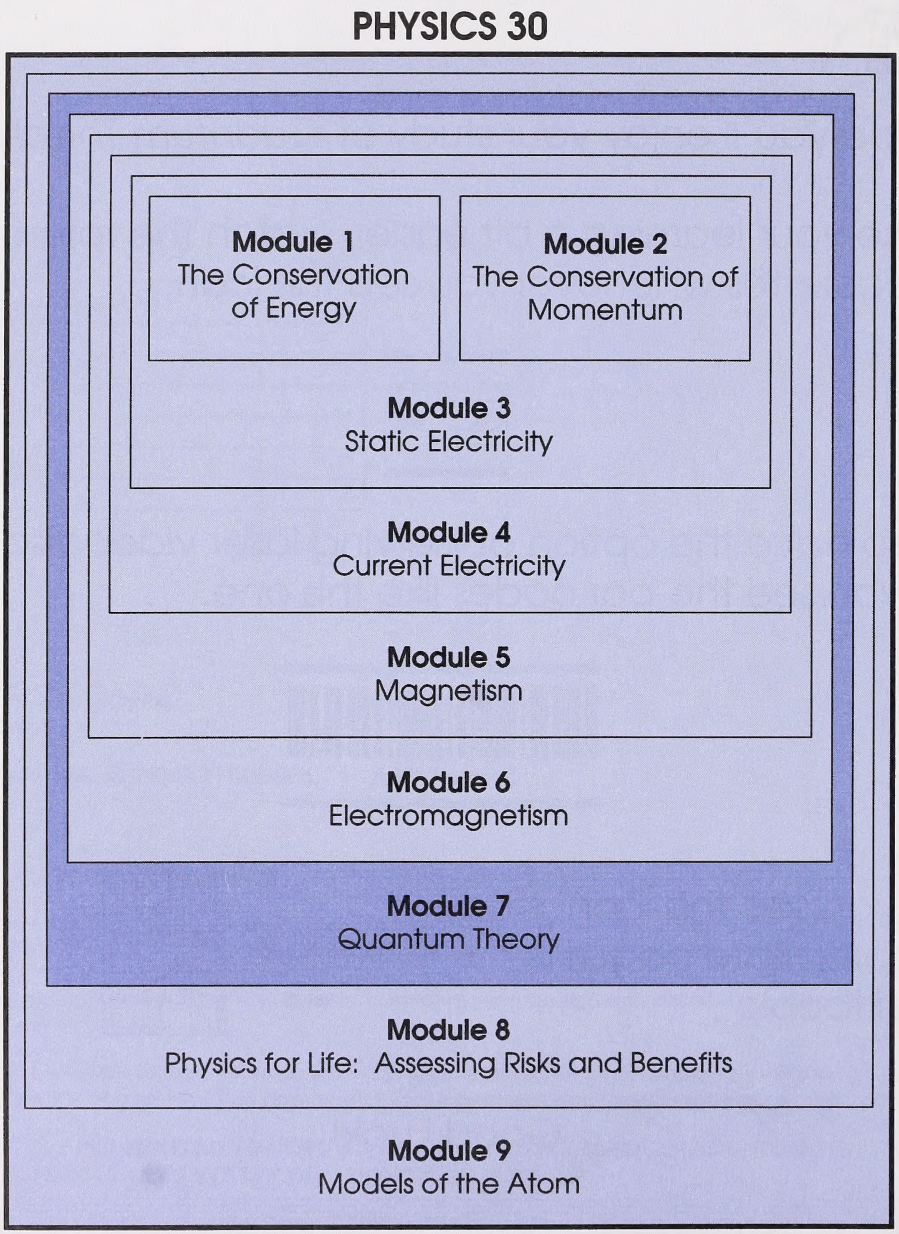


Good Luck!

Course Overview

This course contains nine modules. The first two modules develop the conservation laws of energy and momentum. The conservation of energy is at the heart of the entire course. Modules 3 through 9 build one upon the other and incorporate the main ideas from the preceding modules.

The module you are working in is highlighted in a darker colour.



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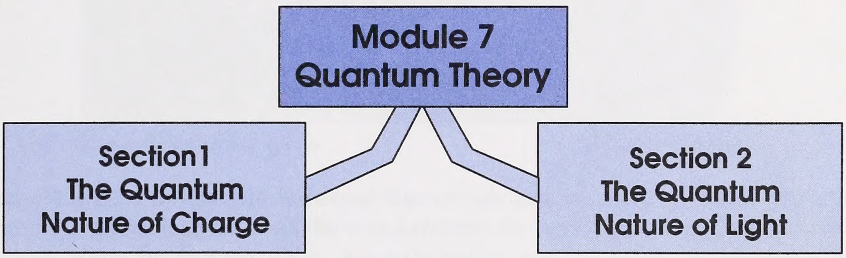
OVERVIEW

When you think of a revolution occurring, what thoughts come to mind? Do you think of the French Revolution with unruly mobs surrounding aristocrats on their way to the guillotine? Perhaps you think of armed rebels using guerrilla tactics as they fight their way into a capital city.

The last three modules of the Physics 30 course are about a revolution that occurred in the first thirty years of the twentieth century, but it's not the kind of revolution that you may have first imagined. The revolution that you'll learn about here is a revolution in science that changed the way that people think about nature and brought about technology that affects every aspect of your life. Television, nuclear weapons, and digital computer technology were all made possible by what some people refer to as the thirty years that rocked physics.

In this module you will be introduced to the revolutionary thinkers who laid the foundation for modern physics. In the first section you will see how the collective work of many physicists led to the discovery of the electron. In the second section you will be introduced to the ideas of Albert Einstein, whose work contributed to a new model for light.



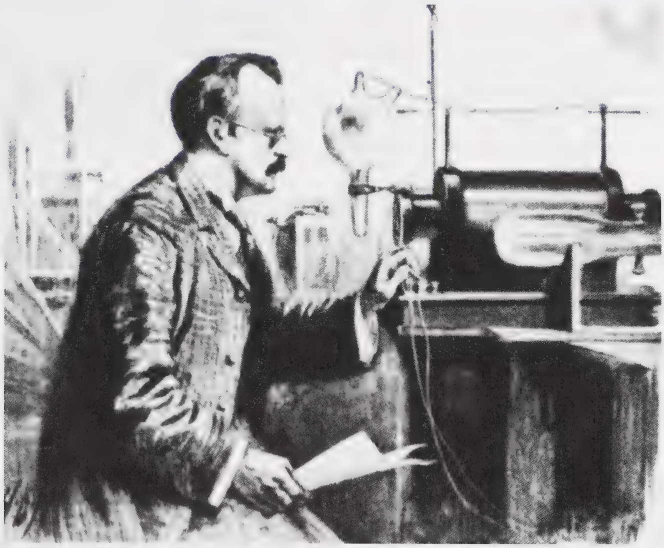
Evaluation

Your mark in this module will be determined by your work in the Assignment Booklet. You must complete all assignments. In this module you are expected to complete two section assignments. The mark distribution is as follows:

Section 1 Assignment	50 marks
Section 2 Assignment	50 marks
TOTAL	**100 marks**

Section

1 The Quantum Nature of Charge



J.J. Thomson and cathode-ray tube THE BETTMANN ARCHIVE

Sometimes it is easy to take fundamental discoveries in science for granted. For example, in the previous modules you used the word *electron* to describe the operation of resistors, motors, and television picture tubes. An early ancestor of the television picture tube, the cathode-ray tube, is shown above, along with Joseph John Thomson. He is the person who is generally credited with the discovery of the electron.

Thomson made significant contributions to the study of subatomic physics. Sometimes his work had a direct impact, like his work with cathode-ray tubes, while at other times it was the people he taught and trained in the Cavendish Laboratory that went on to make the contributions. At least seven of Thomson's research assistants went on to receive Nobel Prizes in physics.

In this section you will retrace the work of J.J. Thomson that led to the idea that electrons are very small particles that carry a negative charge. The techniques used by Thomson will give you a good opportunity to apply some important ideas from earlier in the course. The section ends with an analysis of R.A. Millikan's experiment that determined the charge on one electron. The results of this experiment will provide the first opportunity in the course to begin thinking about the quantum nature of subatomic particles.

Activity 1: Thomson Discovers the Electron

The discovery of the electron by Thomson was made possible by the collective efforts of many scientists. The best way to get a sense of this is to watch a video program that surveys the early work with the atomic model of the atom that paved the way for Thomson's research.

The video series called *The Structure of the Atom* contains a ten-minute program called *The Earliest Models* that presents evidence that supports the atomic model of the atom. Familiarize yourself with the following questions prior to watching the video. This will help you focus on the main ideas while you are viewing. You may have to stop the tape periodically in order to record your answers.

1. The earliest theory of matter developed was the atomism concept of matter. Answer the following questions about the atomism concept.

    a. What is the atomism concept?

    b. Who developed this concept?

    c. What was matter composed of?

    d. How was the atomism concept developed?

2. The alchemists had their own ideas about matter.

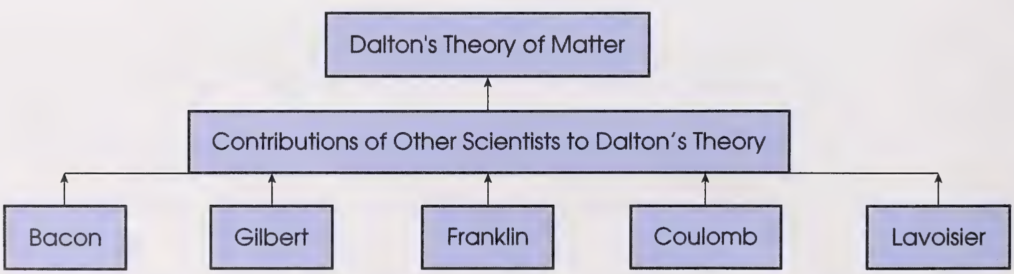
    a. Define transmutation.

    b. Who developed these ideas?

    c. What was matter composed of?

    d. How were these ideas developed?

3. John Dalton used various bits of information to form the common theory of atomic matter. Copy the following chart into your notebook and complete it by writing the major contribution of each scientist below each name.



4. Copy the following headings into your notebook. Be careful to leave enough space under each heading to record your answers. Complete the chart by stating whether each model agrees or disagrees with the statement provided.

	Early Greek Model	Dalton's Model
All matter is made up of atoms.		
Atoms have motion.		
Atoms are indivisible.		
Things differ because of atoms.		

You learned that John Dalton's atomic theory states that atoms are incredibly small particles that cannot be divided into smaller pieces – they are *indivisible*. For most people this tends to evoke mental images of atoms being like tiny indestructible marbles. This was the accepted view throughout the 1800s.

Thomson's work was revolutionary because it changed that idea. Thomson showed that atoms are themselves composed of even smaller particles. You can find out how Thomson came to this conclusion by watching the first part of a video program.

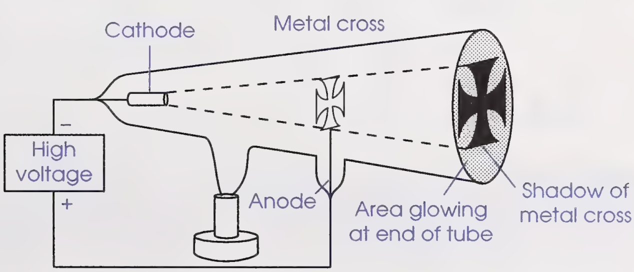
The video series *Structure of the Atom* contains a ten-minute program called *Smaller than the Smallest*. Familiarize yourself with the following questions prior to watching the program. This will help you focus on the main ideas while you are viewing. You may have to periodically stop the tape in order to record your answers.

You will only be watching the first part of this program. When the program starts to discuss the work of R.A. Millikan, stop the tape.

5. What did Faraday think held together the atoms of compounds? What research led to this conclusion?

The following diagram shows the original design of the Maltese cross tube. Refer to this diagram as you answer the questions that follow.

Maltese Cross Tube



6. Why were the mysterious rays that created the shadow of the cross called cathode rays?

7. How do these results indicate that cathode rays travel in straight lines?

8. The metal cross in this tube would have its temperature increased. What does this indicate about the cathode rays?

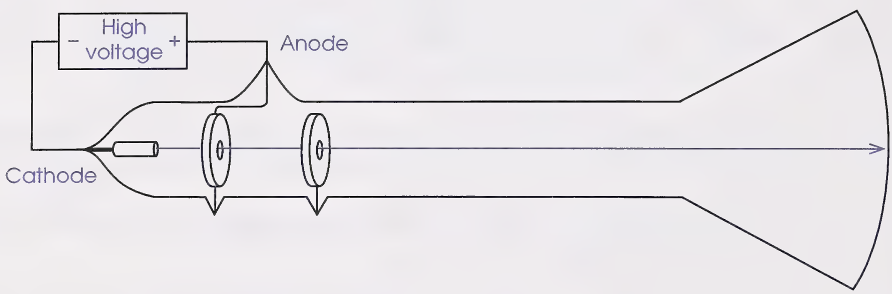
9. What did Crookes think that cathode rays really were? Why couldn't he be sure?

Check your answers by turning to the Appendix, Section 1: Activity 1.

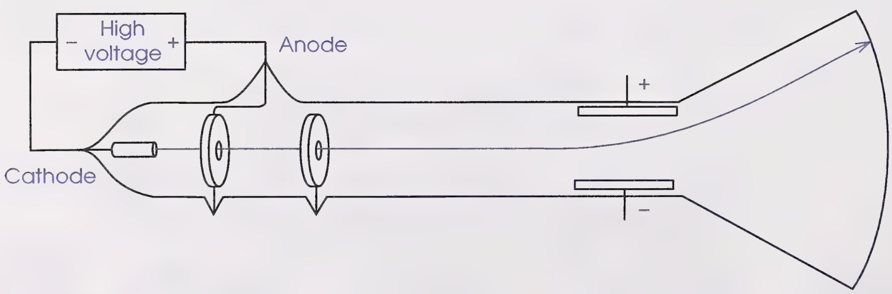
Thomson continued the work of Crookes by designing his own special cathode-ray tube, which is shown in the following diagrams. Refer to these diagrams as you complete the following questions.

Thomson's Apparatus

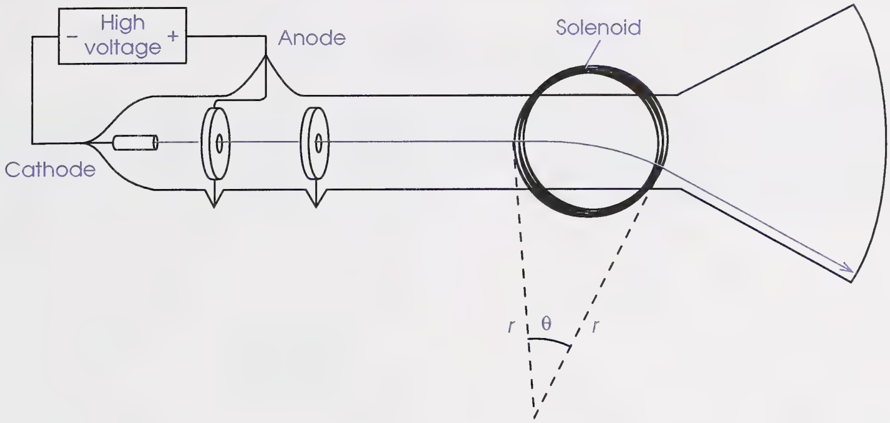
Step 1:



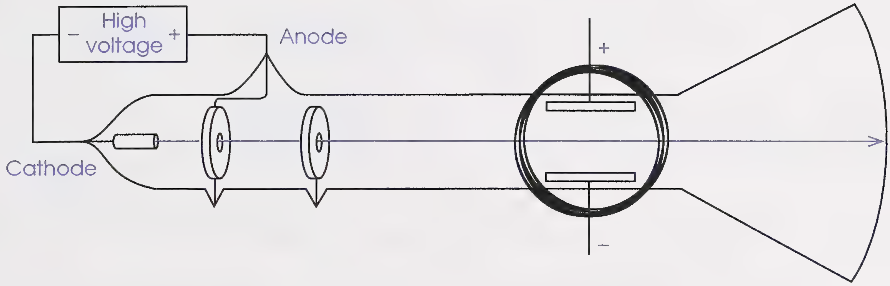
Step 2:



Step 3:



Step 4:



10. Explain what is happening in steps 1 through 4. In each case describe the type of motion that the cathode-ray particles exhibit and discuss any forces involved in the motion.

11. What does the *r* signify in step 3?

12. What was Thomson ultimately able to calculate using this apparatus?

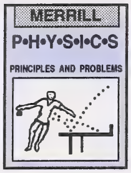
13. What evidence suggested to Thomson that cathode-ray particles were a fundamental component of all matter?

14. What name was eventually given to cathode-ray particles?

Stop the videotape when the description of R.A. Millikan's work begins.

Check your answers by turning to the Appendix, Section 1: Activity 1.

Although the computer animation on the videotape gave you valuable insight into how Thomson's experiment worked, it did not explain the details of how he calculated the charge-to-mass ratio $\left(\frac{q}{m}\right)$. You can find out how Thomson did this by reading from the top of page 536 to the middle of page 537 in your textbook.



15. Figure 26-1(b) on page 536 of your textbook accidentally left out an important part of Thomson's apparatus. What part is missing?

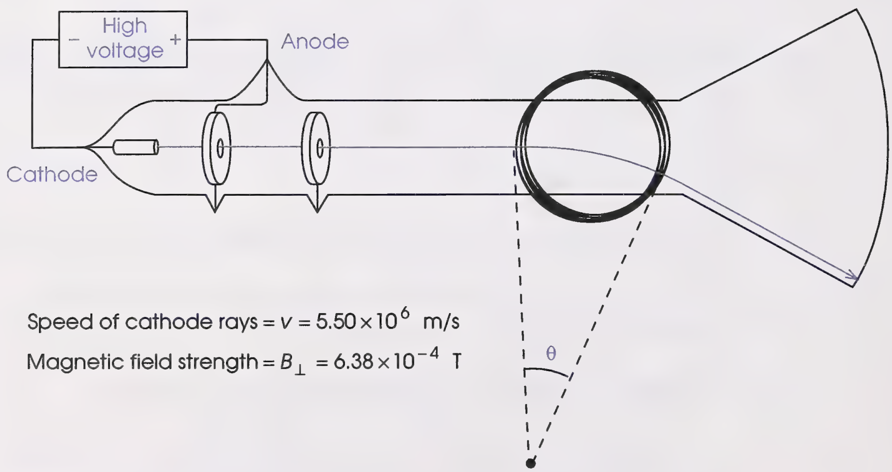
16. Draw a flow chart to illustrate how Thomson calculated the speed of the cathode rays. Be sure to add the necessary steps and explanations to make the flow chart clear. Start the flow chart with the step shown.

$$\boxed{F_m = F_e}$$

17. Draw a flow chart to show how Thomson calculated the charge-to-mass ratio for the cathode-ray particles. Be sure to add all the necessary steps and explanations to make the flow chart clear. Start the flow chart with the step shown.

$$\boxed{F_m = F_c}$$

18. Treat the following diagram as a true-size drawing of Thomson's apparatus. The magnetic force caused the beam to be deflected.



Speed of cathode rays $= v = 5.50 \times 10^6$ m/s

Magnetic field strength $= B_\perp = 6.38 \times 10^{-4}$ T

a. Use the diagram and the data provided to calculate the charge-to-mass ratio of these cathode-ray particles.

b. Determine the direction of the magnetic field created by the coil.

Check your answers by turning to the Appendix, Section 1: Activity 1.

You may have noticed that the flow charts that you completed in the previous questions began with a statement about forces and then included a substitution of equations from the Physics 30 data sheets. This is the way that you should begin to solve problems. Unfortunately, the textbook tends to leave out the initial statement about forces when it shows Example Problems and solutions. Keep this in mind as you read from the last three lines on page 537 to the bottom of page 538 of your textbook.

19. In an experiment similar to Thomson's, cathode-ray particles were observed to move through a radius of curvature of 0.114 m when a magnetic field of 1.01×10^{-3} T acted alone. However, when the deflecting plates were properly adjusted, the ray of cathode particles was observed to be undeflected. The deflecting plates were 1.00 cm apart and the potential difference across them was 200 V. Calculate the charge-to-mass ratio.

20. Do Practice Problem 4 on page 539 of your textbook.

Check your answers by turning to the Appendix, Section 1: Activity 1.

mass spectrometer – a device used to determine the masses of atoms or molecules

Thomson's apparatus has since been modified to be a valuable analytical tool known as a **mass spectrometer**. To find out how the mass spectrometer works, read from the middle of page 539 to the bottom of page 541 of your textbook.

21. Refer to Figure 26-3 on page 539 of your textbook. Use Newton's laws to explain why ions with larger masses have larger radii of curvature.

22. Use a flow chart to derive the equation $\frac{q}{m} = \frac{2V}{B_{\perp}^{2} r^{2}}$. Be sure to add all the necessary steps.

23. The second last paragraph on page 540 of the textbook explains that the distance between the mark on the photographic film and the hole in the electrode is actually twice the radius of the circular path. Draw a diagram to help explain why this is the case.

24. Give one example of how a mass spectrometer could be used by industry.

Check your answers by turning to the Appendix, Section 1: Activity 1.

25. Do Practice Problems 5 and 8 on pages 541 and 542 of your textbook.

26. Do Problem 9 on page 553 of your textbook. Be sure to start your solution with equations from the Physics 30 data sheets.

Check your answers by turning to the Appendix, Section 1: Activity 1.

In the next activity you will see how Thomson's results were used by Robert A. Millikan to calculate the mass of an electron.

Activity 2: Millikan Measures Electron Charge

Thomson's achievement was to prove beyond a doubt that cathode rays consisted of a stream of negatively charged particles (electrons). However, the mass and charge of a single electron was still a mystery because he found the **ratio** of these two quantities, not the individual values.

$$\boxed{\frac{q}{m} = 1.76 \times 10^{11} \text{ C/kg}}$$

The only way to account for such a large value for this ratio is to assume that either the charge on a single electron is very large or the mass is very small. Thomson suspected that the mass was about $\frac{1}{1800}$ of the mass of a hydrogen atom, but he could not prove it. It was not until Robert A. Millikan, an American physicist, calculated the charge on one electron that Thomson's estimate could be verified.


BETTMANN

Millikan made significant contributions to the field of physics. The photograph shows Millikan (on the right) and an assistant looking over his self-recording electroscope, a device used to study cosmic rays (mainly protons but also some high-energy gamma rays from deep space).

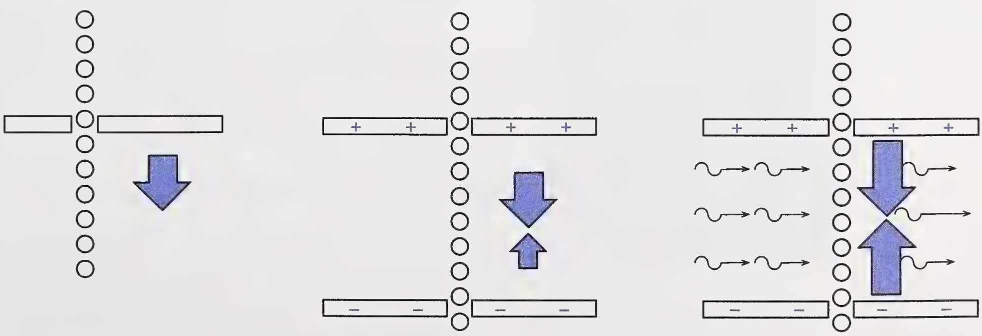
Millikan's work with the electron involved an experiment that had a simple yet very effective design that allowed him to determine the charge on one electron. You can find out more about this experiment by watching the last part of the video program that you started in the last activity.

The video series *Structure of the Atom* contains a ten-minute program called *Smaller than the Smallest*. If necessary, fast-forward to the last part of the program where the work of Millikan is described. Familiarize yourself with the following questions prior to watching the program. This will help you focus on the main ideas while you are viewing. You may have to periodically stop the tape in order to record your answers.

The following diagrams describe the basic design of Millikan's experiment. Refer to these diagrams of microscopic oil droplets falling through a pin hole as you answer the questions that follow.

Millikan's Apparatus

Step 1: Step 2: Step 3:



1. What force does the downward arrow represent in step 1?

2. Since the space that the oil droplets fall through is not a vacuum, what other force should be considered?

3. What force does the upward arrow represent in step 2?

4. What does your answer to the previous question indicate about the sign of the charge on the oil droplets?

5. What do the small horizontal arrows represent in step 3?

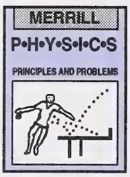
6. Explain why the upward arrow is larger in step 3 than it is in step 2. Refer to your responses to the previous questions to help support your answer.

7. Describe the process used by Millikan to deduce the charge on one electron.

8. How did Thomson use Millikan's result to form a new model of the atom? Was this model successful?

Stop the videotape when the program ends.

The videotaped program used computer animation to give an effective overview of Millikan's experiment. However, the program did not go into the details of the equations. Once again, your textbook is a valuable source of information in this area.



Carefully read from the top of page 436 to the end of the second paragraph on page 437 in your textbook.

9. Copy the following headings into your notebook. Be careful to leave enough space under each heading to record your answers. Complete the chart by describing which force is larger and what the direction of the net force should be.

Motion of Oil Droplet Between the Plates	Is $\vec{F}_g$ or $\vec{F}_e$ larger?	What is the direction of the net force?
Accelerating Down		
Suspended (at rest)		
Accelerating Up		
Uniform Motion Up or Down		

10. Explain how the mass of a single oil drop was determined by Millikan.

11. According to Millikan's results, is it possible for an object to have a charge of -1.0×10^{-19} C? Explain concisely.

Check your answers by turning to the Appendix, Section 1: Activity 2.

At the heart of Millikan's method is a data analysis technique that looks for changes in a collection of data. You can gain insight into this by completing the next investigation which simulates Millikan's data analysis method.

Investigation: Simulating Millikan's Data Analysis

Science Skills

- ☐ A. Initiating
- ☑ B. Collecting
- ☑ C. Organizing
- ☑ D. Analysing
- ☐ E. Synthesizing
- ☐ F. Evaluating

Purpose

In this investigation you will use steel ball bearings and an electronic balance to simulate Millikan's work.

PATHWAYS

If you have access to laboratory facilities, do Part A.
If you do not have access to laboratory facilities, do Part B.

Part A

Materials

You will need the following materials to complete this investigation:

- a sensitive balance (preferably electronic)
- at least fifty identical ball bearings or fifty identical coins (pennies)
- a small container to hold the ball bearings or coins

Procedure

Follow the procedure given in the Pocket Lab in the margin on page 436 of your textbook. You should do at least five trials instead of the three asked for in the textbook.

Data

12. Record the total mass of the ball bearings for each trial in a chart. The steps for the analysis of the data can be found at the end of Part B.

End of Part A

Part B

Procedure

You will be provided with sample data collected from the procedure described in Part A. To understand how the data was collected, read through the procedure for Part A before continuing.

Data

Total Mass of an Unknown Number of Ball Bearings						
Trial	1	2	3	4	5	6
Mass (g)	151	250	449	76	474	326

End of Part B

Analysis and Interpretation

13. How did Millikan determine that the smallest charge was 1.60×10^{-19} C?

14. How are you going to determine the value for the mass of one ball bearing?

15. You were making an assumption when you answered the previous question. What is that assumption?

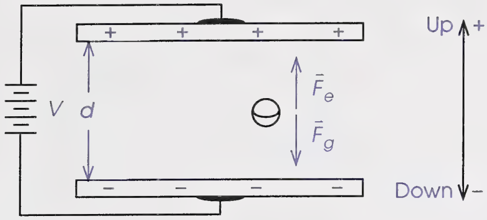
16. Find the mass of one ball bearing.

Conclusions

17. Could the actual unit mass be smaller or larger than the value you found in the previous question? Explain.

Check your answers by turning to the Appendix, Section 1: Activity 2.

Now that you have an idea of how Millikan analysed his data, you can take a look at the vector force analysis that describes a suspended oil drop.



$$\vec{F}_{net} = \vec{F}_e + \vec{F}_g = 0$$

$$\left|\vec{F}_e\right|_{up} + \left|\vec{F}_g\right|_{down} = 0$$

$$+\left|\vec{F}_e\right| - \left|\vec{F}_g\right| = 0$$

$$\left|\vec{F}_e\right| = \left|\vec{F}_g\right|$$

$$\left|\vec{E}\right| q = mg$$

$$\frac{V}{d} q = mg$$

18. Using the equations given, find an equation for the charge on a suspended oil drop.

19. Do Practice Problems 9 and 10 on page 437 of your textbook. Be sure to begin your solutions with the recommended approach.

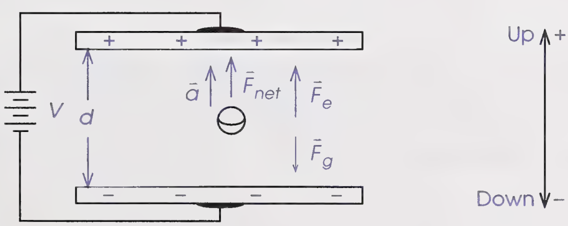
MERRILL P•H•Y•S•I•C•S PRINCIPLES AND PROBLEMS

Check your answers by turning to the Appendix, Section 1: Activity 2.

It is important to start solutions with a vector description of forces because sometimes the oil droplets are not suspended since the net force is not zero. In these cases the droplets will accelerate between the plates in the direction of the unbalanced force. The following example shows how to begin solving this kind of problem.

Example

An oil droplet with a mass of 5.00×10^{-16} kg accelerates upwards between two charged metal plates at $2.20\ \text{m/s}^2$. The plates are separated by 3.00 cm and have a potential difference of 9.00 V across them. Calculate the charge on the oil droplet.



$m = 5.00 \times 10^{-16}$ kg

$\vec{a} = +2.20\ \text{m/s}^2$

$V = 9.00$ V

$d = 3.00$ cm

$q = ?$

Since this is a vector problem, it is essential to begin with a sign convention.

Solution

$$\vec{F}_{net} = \vec{F}_e + \vec{F}_g$$

$$\left|\vec{F}_{net}\right|_{up} = \left|\vec{F}_e\right|_{up} + \left|\vec{F}_g\right|_{down}$$

$$\left|\vec{F}_{net}\right| = \left|\vec{F}_e\right| + \left(-\left|\vec{F}_g\right|\right)$$

$$ma = q\left|\vec{E}\right| - mg$$

$$ma = q\left(\frac{V}{d}\right) - mg$$

20. Rearrange the last equation to isolate the charge.

21. Calculate the charge on the oil drop using the data provided.

22. A negatively charged oil drop with a mass of 6.30×10^{-16} kg is observed to accelerate downward at $1.00\ \text{m/s}^2$ between two parallel plates. The plates were separated by 75.5 mm and had a potential difference of 26.19 V across them.

    a. Draw a diagram that concisely shows the relevant data with an appropriate sign convention.

    b. Starting with a vector description of the forces acting on the oil droplet, solve for the magnitude of the charge on the oil drop.

    c. How many excess electrons must be on this oil drop?

Check your answers by turning to the Appendix, Section 1: Activity 2.

Millikan's work had many implications. The most obvious is that his value for charge could be combined with Thomson's charge-to-mass ratio to determine the mass of one electron.

23. Use the charge-to-mass ratio for electrons $\left(1.76 \times 10^{11}\ \text{C/kg}\right)$ and Millikan's value for charge to calculate the mass of one electron. Compare your answer to the value given in the Physics 30 data sheets.

24. Thomson used his apparatus to determine the charge-to-mass ratio for ionized hydrogen (a proton). Thomson discovered that the charge-to-mass ratio for ionized hydrogen was 1836 times smaller than the value for an electron. If Thomson assumed that the proton had a positive value of the same charge as the electron, what value could he calculate for the mass of a proton? Compare your answer with the value given in the Physics 30 data sheets.

The real impact of Millikan's work is the insight it provided into the workings of nature on the atomic and subatomic scale. Electricity, for example, is no longer considered to be a continuous fluid as Franklin had originally described it, but rather involves charges that can only have values that are exact whole number multiples of the charge on one electron. In other words, charge is **quantized**. The fundamental amount of charge is 1.60×10^{-19} C, which could be called the **quantum** for charge. Since electrons cannot be cut in half or quarters, the quantum for charge is the smallest charge that can ever exist.

quantized – made up of multiples of some fundamental quantum value

Charge is not the only thing that is quantized. When dealing with things on the atomic scale, nature seems to have many quantized things.

quantum – the smallest value that can exist for a quantity. All other values are multiples of this fixed amount.

25. What is the quantum for the element iron? Explain your answer.

Check your answers by turning to the Appendix, Section 1: Activity 2.

In the next section you will discover that light itself is quantized. The quantum for light is an exceptionally useful idea that helps to explain a wide variety of phenomena.

Follow-up Activities

If you had difficulties understanding the concepts in the activities, it is recommended that you do the Extra Help. If you had a clear understanding of the concepts, it is recommended that you do the Enrichment.

Extra Help

In this section you have seen how two very important experiments led to the discovery of the electron. When solving problems related to these experiments, the first step is to make a statement about forces and then let the solution proceed from that point.

Copy the following headings into your notebook. Be careful to leave enough space under each heading to record your answers. Complete the chart by adding the missing information under each heading.

Name of Experiment or Apparatus	Description of What Is Happening to the Charged Particle	Related Force Equations
		$F_e = F_m$ $q\lvert\vec{E}\rvert = qvB_{\perp}$
	The charged particle is forced to move in a circle. The magnetic force is providing the centripetal force necessary for circular motion.	
		$\vec{F}_{net} = \vec{F}_e + \vec{F}_g = 0$ $\lvert\vec{F}_{net}\rvert = q\lvert\vec{E}\rvert - mg = 0$ $q\left(\frac{V}{d}\right) = mg$
		$\vec{F}_{net} = \vec{F}_e + \vec{F}_g \neq 0$ $\lvert\vec{F}_{net}\rvert = \lvert\vec{F}_e\rvert + \lvert\vec{F}_g\rvert$ $ma = q\lvert\vec{E}\rvert - mg$

Check your answers by turning to the Appendix, Section 1: Extra Help.

Enrichment

Choose **one** of the following activities.

1. If you have access to the Laboratory Manual that accompanies the textbook, a complete mass-of-the-electron apparatus, and a supervised science lab, do the investigation called Mass of an Electron in the Laboratory Manual.

MERRILL P•H•Y•S•I•C•S PRINCIPLES AND PROBLEMS

2. Read the Physics and Technology section on page 417 of your textbook. When you have finished reading this section, do the following questions.

   a. Why do photocopies feel warm when they come out of the machine?

   b. Why do photocopies often stick together when they first leave the machine?

   c. Why does the drum of the photocopier need to be coated with a semiconducting material rather than a substance that is a perfect conductor?

Check your answers by turning to the Appendix, Section 1: Enrichment.

Conclusion

In this section you have seen how the charge-to-mass ratio, the charge, and the mass of an electron were eventually determined. The charge of the electron is an example of how nature tends to quantize values on the atomic and subatomic scales. In the next section you will examine another example of quantization as you investigate the quantum for light.

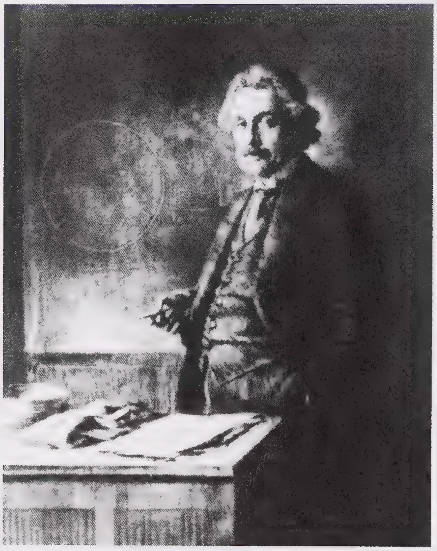
Assignment Booklet

ASSIGNMENT

Turn to your Assignment Booklet and do the assignment for Section 1.

Section

2 The Quantum Nature of Light



Albert Einstein THE BETTMANN ARCHIVE

Albert Einstein took such a long time learning to speak as a young child that his parents feared that he might be mentally handicapped. In high school he was interested only in mathematics and found Latin and Greek very difficult. He eventually dropped out of high school at the recommendation of a teacher who supposedly said, "You'll never amount to anything, Einstein."

Einstein eventually enrolled in a college and had great difficulty passing because he spent most of his time reading about the latest discoveries in theoretical physics. After he graduated in 1901, his father used his influence to get his son a job as a clerk in the Swiss Patent Office.

In 1905 Einstein had five of his scientific papers published in the *German Yearbook of Physics*. The third of these five papers revolutionized the world of physics with his theory of special relativity, but it was the first of these papers that eventually earned him his Nobel Prize in 1921. This paper proposed a quantum model of light in an attempt to explain a puzzling set of observations known as the photoelectric effect.

In this section you will discover how the photoelectric effect provided Albert Einstein with the starting point for a new model for light. You will have opportunities to apply these ideas in investigations and solving problems. By the time the section ends, you will have combined what you learned here with the key concepts from Section 1 to develop a new outlook on the nature of the subatomic world.

Activity 1: The Photon Model

You've probably heard the term *red hot* used to describe something that is at a very high temperature. Do you think that it is possible for things to get *green hot* or *violet hot*?

You can answer this question by reading from the top of page 555 to the bottom of the fourth paragraph on page 556 of the textbook.

1. Does the term *red hot* indicate that an object has the highest temperature possible?

2. What happens to objects as their temperature becomes higher and higher? Do they ever become violet hot?

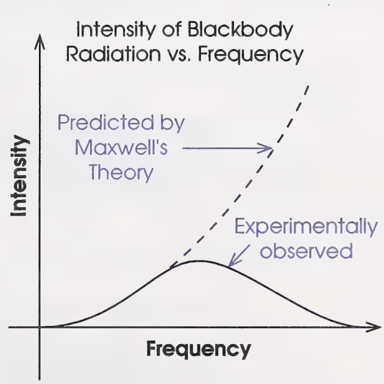
Check your answers by turning to the Appendix, Section 2: Activity 1.

Figure 27-1 on page 556 shows how the intensity varies with the frequency of the light emitted from an object that is heated to a given temperature. The objects heated were not reflecting and appeared black at room temperature. This is why the light emitted is referred to as **blackbody radiation**.

blackbody radiation – radiation from a hot and luminous body that absorbs all the radiation that falls on it

3. Explain how the surface of the sun can have a temperature of 5800 K and appear yellow even though the peak of the 5800 K curve does not reach its peak above the colour yellow.

The graphs shown in Figure 27-1 have a distinct shape. Why do they have this particular curve? This is a question that physicists attempted to answer during the 1890s. The trouble was that Maxwell's theory of electromagnetic radiation, which was the accepted model for light, could not explain the shape of these graphs. Even worse, Maxwell's theory predicted an entirely different type of curve that was never observed.



According to Maxwell's theory, visible light was produced by accelerating charges. The higher the frequency of vibration, the higher the frequency of the light emitted. It follows from this that substances raised to higher and higher temperatures have their molecules vibrating at increasingly higher frequencies and should therefore emit light with increasing frequencies.

In other words, Maxwell's theory predicted that very hot objects should be emitting much more blue and violet light than they actually do. This problem became known to physicists as a *violet catastrophe* because the current theory did not match the observations.

To solve the problem, Max Planck, a German physicist, proposed a new model for the way that atoms emit light. At the heart of Planck's proposal was the idea that atoms can emit energy only in bundles. He called each bundle a quantum. He suggested that the energy of each bundle is proportional to the frequency of electromagnetic radiation produced. This is summarized in the following equation.

Energy of the quantum → $\boxed{E = hf}$ ← Frequency of the radiation emitted

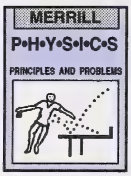
Planck's constant: $h = 6.63 \times 10^{-34}$ J • s

Planck's constant – ratio of the energy of a photon to its frequency

4. Which will have more energy, a quantum of red light or a quantum of violet light? Explain concisely.

5. In order for a hot object to emit red light, enough energy must be brought together to form a quantum of red light energy. Why is it more plausible that hot objects will emit red light rather than violet light?

6. Is your answer to the previous question consistent with Figure 27-1 on page 556 of your textbook?



You can gain greater insight into Planck's ideas by reading the last paragraph on page 556.

7. Explain the meaning of the variables in the equation $E = nhf$. Also explain how this equation relates to the equation $E = hf$.

8. What does it mean to say that energy is *quantized*?

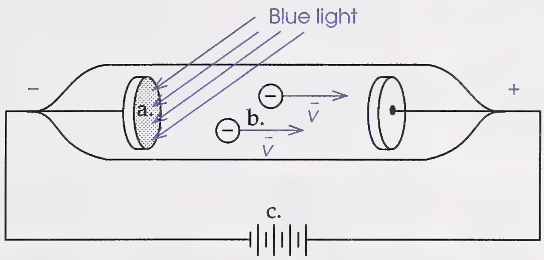
Check your answers by turning to the Appendix, Section 2: Activity 1.

The ideas of Max Planck were used by Albert Einstein to create a new model for light. You can learn more about this model and the experiments that precipitated it by watching a video program.

The video series *Wave Particle Duality* contains a ten-minute program called *The Quantum Idea*. Familiarize yourself with the following questions prior to watching the program. This will help you focus on the main ideas while you are viewing. You may have to periodically stop the tape in order to record your answers.

photoelectric effect – Electrons are liberated from a surface due to the presence of electromagnetic radiation.

9. The following diagram shows the key parts in a **photoelectric effect** apparatus. Each part has been labelled with a letter. Describe the role and function of each part labelled with a letter in the apparatus.



10. Refer to the diagram shown in the previous question.

    a. How would this diagram have to be changed if red light was used instead of blue light?

    b. Would your answer to question 10.a. differ if the red light was very intense?

    c. How would the diagram change if the blue light was made more intense?

    d. How would the diagram change if higher frequency violet light was used instead of blue light?

11. How did Einstein explain the difference between red light and blue light striking the potassium-coated electrode? Refer to the equation $E = hf$ in your answer.

12. Explain Einstein's prediction that higher frequency light quanta will cause the emission of electrons with greater energy.

13. Explain Einstein's prediction that more intense light should cause an increased electron flow.

14. What name was given to the bundles of light energy in Einstein's model?

Stop the videotape when the program comes to the end.

Check your answers by turning to the Appendix, Section 2: Activity 1.

It was Einstein's theory for the photoelectric effect that earned him his Nobel Prize in 1921. You can learn more about Einstein's theory by reading the last three paragraphs on page 557 up to the first paragraph on page 559 of your textbook.

15. Why are the electrons in the photoelectric effect called photoelectrons? How do they differ from the electrons studied by Thomson and Millikan?

16. What is the threshold frequency?

17. What variable determines the value of the threshold frequency?

18. Think back to the explanation of the photoelectric effect given on the video program. What colour of light represented the threshold frequency in that program?

19. List the assumptions made by Einstein in explaining the photoelectric effect.

20. Construct a flow chart to show the origin of the equation $E_k = hf - hf_o$.

Check your answers by turning to the Appendix, Section 2: Activity 1.

It is important to realize that Einstein's equation for the photoelectric effect $\left(E_k = hf - hf_o\right)$ was originally proposed as a theory to explain qualitative observations. The equation itself needed to be tested quantitatively to determine if the theory was valid. This means that both the frequency of the incident light and the kinetic energy of the ejected photoelectrons needed to be measured in a working apparatus.

The difficult quantity to measure is the kinetic energy of the ejected photoelectrons. You should read the procedure for an indirect measurement of this kinetic energy described in the last two paragraphs and the Example Problem on page 559 of your textbook. Note that you should not include the negative sign in the equation because you do not substitute the sign of the charge into equations.

21. What is the stopping potential (or stopping voltage)?

22. What is an electron volt?

23. Do Practice Problems 1 and 2 on page 561 of your textbook.

Check your answers by turning to the Appendix, Section 2: Activity 1.

The two most important tests of Einstein's theory were the following two questions:

- Is the maximum kinetic energy of the ejected photoelectrons proportional to the frequency of the incident light?
- Is the constant h the same for all substances that are used to coat the surface of the cathode?

Robert Millikan answered these questions by carefully collecting and graphing data for a photoelectric experiment. His thoughts are summarized by the following flow chart.

$$E_k = hf - \underbrace{hf_o}$$

By inspection

$$y = mx + \overbrace{b}$$

You can see a graph produced by this type of experiment at the top of page 560 in your textbook. Study this graph and read the description and Example Problems on pages 560 and 561 of your textbook. Questions 24 to 28 refer to the graph shown on page 560.

24. What feature of the graph corresponds to Planck's constant?

25. Use the graph to determine an experimental value for Planck's constant.

26. What feature of the graph does the previous flow chart say should correspond to the work function?

27. How would you have to determine the work function from the graph? Explain your answer.

28. Determine the work function for the metal that was used to collect data for the graph. Express your answer in electron volts.

Check your answers by turning to the Appendix, Section 2: Activity 1.

You should be aware that the equations for the photoelectric effect in the Physics 30 data sheets are slightly different than those in the textbook. Of course the underlying physics is the same, but you should use the equations shown in the Physics 30 data sheets.

29. Label each of the variables in the following equations.

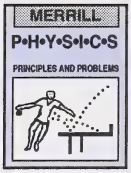
a. $hf = E_{k_{max}} + W$

b. $W = hfo$

c. $E_{k_{max}} = qV_{stop}$

d. $E = hf = \dfrac{hc}{\lambda}$

30. Use the equations from the Physics 30 data sheets to solve Practice Problems 3 and 4 on page 561 of your textbook.



31. Use the equations from the Physics 30 data sheets to solve Problems 10.a. and 11.a. on page 571 of your textbook.

32. A metal surface is illuminated with blue light that has a wavelength of 455 nm. If the work function of the metal surface is 2.49 eV, calculate the maximum speed of the ejected electrons.

33. Ultraviolet light with a wavelength of 250 nm shines on a metal surface. Photoelectrons with maximum kinetic energy 1.10 eV are emitted. Calculate the work function of this metal surface.

Check your answers by turning to the Appendix, Section 2: Activity 1.

In the next activity you will have an opportunity to experimentally determine the value for Planck's constant.

Activity 2: Photons at Work for You

light-emitting diode – a semiconductor device that can emit light when current passes in the right direction

LED – abbreviated term for light-emitting diode

Up to this point your study of the photon model of light has been a careful examination of famous experiments and the theories that support them. Now it is time for you to do your own experimental work and to apply some of these key concepts. The next investigations will provide you with these opportunities.

The key component to be used in the investigations is called a **light-emitting diode**, or **LED**. Diodes are devices that allow conventional current to flow in only one direction through them. In the past diodes were constructed in the form of an electron vacuum tube, but now, in all but special applications, the vacuum-tube diode has been replaced by the **semiconductor** diode.

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Examine the photograph on page 594 and read the description on page 595 of your textbook.

1. List some reasons why the electron vacuum-tube diode was replaced by the semiconductor diode.

The type of diode that you will use is called a light-emitting diode because it emits light when current passes through it in the proper direction. LEDs are often used on control panels of electronic devices to display information. Sometimes the display involves the LEDs forming a bar graph, as on the graphic equalizer display of a stereo, while other applications require the LEDs to form numbers, as in certain types of clock radios.

The reason that LEDs are so useful for this part of the course is that they have the property of emitting light within a narrow band of wavelengths, with one wavelength being the brightest. It is this property of LEDs that will eventually allow you to use them to calculate Planck's constant.

In the next investigation you will explore the properties of LEDs.

Investigation: Exploring the Properties of LEDs

Science Skills

- ☐ A. Initiating
- ☑ B. Collecting
- ☑ C. Organizing
- ☐ D. Analysing
- ☐ E. Synthesizing
- ☐ F. Evaluating

Purpose

In this investigation you will verify some of the properties of LEDs using Physics 30 concepts.

Important Safety Precautions

Caution

It is very important that you read and apply the information in these safety warnings before you begin this investigation. Injury or death can occur even with low voltages and low currents.

- Never ground yourself while working with a live circuit. Do not touch metal pipes, electric outlets, light fixtures, etc., that might be grounded. Be sure to keep your body insulated by keeping your hands and body dry and by wearing dry clothing and running shoes.

- Only replace the fuse inside the meter with the specified or approved equivalent fuse.

- Use the meter only as specified in the investigation. Do not use the meter to test a wall outlet or an electric appliance. If you try to measure a voltage that exceeds the limits of the meter, you may damage the meter and expose yourself to a serious electric shock.

- Resistors can become warm and in some cases hot enough to cause burns. Always disconnect a recently used resistor and allow it to cool for a few minutes before handling.

You will ensure your own safety by applying this information as you complete the investigation.

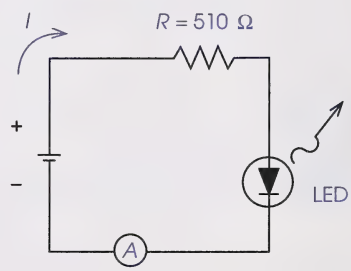
Materials

You will need the following materials for this investigation:

- three LEDs: one red, one green, and one amber
- a variable low-voltage DC power supply with a range of approximately 5 V to 20 V
- a 510-Ω resistor rated at 0.5-W power handling (The stripes on this resistor will be green, brown, brown, gold.)
- four wire connectors with alligator clips at each end
- a multimeter capable of measuring 0 mA to 30 mA or an ammeter with this range

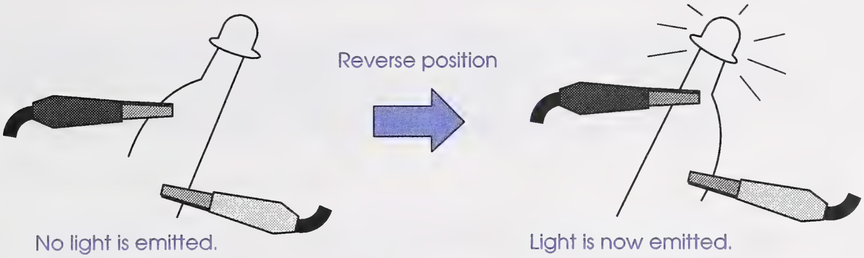
Procedure

- Without turning on the low-voltage power supply, build the circuit shown in the following photograph and schematic diagram. Use the red LED.



- Inspect the circuit to check that all the connections with the alligator clips are secure, the multimeter is properly set up, and the resistor is in series with the red LED.
- Adjust the power supply to provide an output of about 5 V and then turn it on to supply voltage to the circuit.

- Observe the LED. Is it emitting light? If it is not, disconnect the LED and reconnect it in the reverse position. This should cause the LED to emit light.



If the LED still does not light, check to see if the power supply is working and that you have good connections around the circuit. If that still doesn't work, try another LED.

- The LED should now be emitting red light.

2. What current is being displayed on the ammeter?

- Disconnect the LED and reverse its position so that it does not emit light.

3. What current is being displayed on the ammeter now?

4. Explain how the answers to the previous two questions support the definition of a light-emitting diode.

5. Re-examine the schematic diagram of the circuit and compare the direction of conventional current, *I*, to the direction of the arrow on the symbol for the LED. Why do you think LEDs are given this symbol?

- Gradually increase the voltage to a maximum value of 18 V and observe the changes in the light emitted by the LED and in the current being displayed on the meter.

6. Use the photon model of light to explain the relationship between current and light intensity.

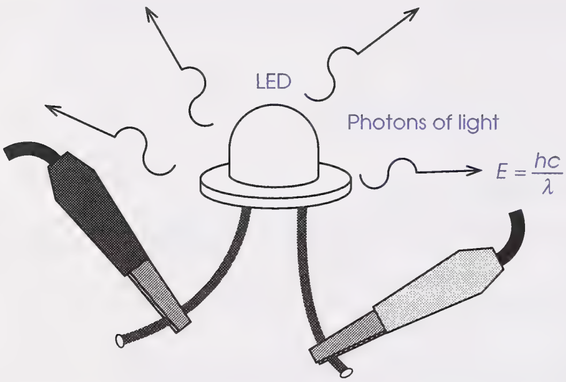
- Test the amber and green LEDs to ensure that they work and that they have similar properties to the red LED.

Conclusions

7. List two properties of LEDs that you verified in this investigation.

Check your answers by turning to the Appendix, Section 2: Activity 2.

Now that you know a little bit more about LEDs, you can start to think about how the LED can be used to obtain a value for Planck's constant.



The LED is emitting photons that each have an energy given by Einstein's equation $E = \frac{hc}{\lambda}$.

8. What values need to be measured to determine Planck's constant from the previous equation?

Check your answers by turning to the Appendix, Section 2: Activity 2.

The answer to the previous question indicates that the energy of a photon will have to be determined. Recall from your work with circuits in Module 4 that the practical way to keep track of energy transfer in a circuit is to use potential difference, since this is easily measured in terms of voltage.

In the next investigation you will use the relationship between potential difference and current to obtain an estimate of the average energy possessed by the photons of the LED. This value will then be combined with a wavelength value for the LED to determine an experimental value for Planck's constant.

Investigation: Calculating Planck's Constant

Purpose

In this investigation you will use graphical analysis to obtain an experimental value for Planck's constant.

Caution

Important Safety Precautions

It is very important that you read and apply the information in these safety warnings before you begin this investigation. Injury or death can occur even with low voltages and low currents.

- Never ground yourself while working with a live circuit. Do not touch metal pipes, electric outlets, light fixtures, etc., that might be grounded. Be sure to keep your body insulated by keeping your hands and body dry and by wearing dry clothing and running shoes.

- Only replace the fuse inside the meter with the specified or approved equivalent fuse.

- Use the meter only as specified in the investigation. Do not use the meter to test a wall outlet or an electric appliance. If you try to measure a voltage that exceeds the limits of the meter, you may damage the meter and expose yourself to a serious electric shock.

- Resistors can become warm and in some cases hot enough to cause burns. Always disconnect a recently used resistor and allow it to cool for a few minutes before handling.

You will ensure your own safety by applying this information as you complete the investigation.

Materials

You will need the following materials for this investigation:

- three LEDs: one red, one green, and one amber

- a variable low-voltage DC power supply with a range of approximately 5 V to 20 V

- a 510-Ω resistor rated at 0.5-W power handling (The stripes on this resistor will be green, brown, brown, gold.)

- four wire connectors with alligator clips at each end

- a multimeter capable of measuring 0 mA to 30 mA*, and 0 V to 20 V, DC*

(*A voltmeter and an ammeter with these ranges can be used for this investigation.)

Procedure

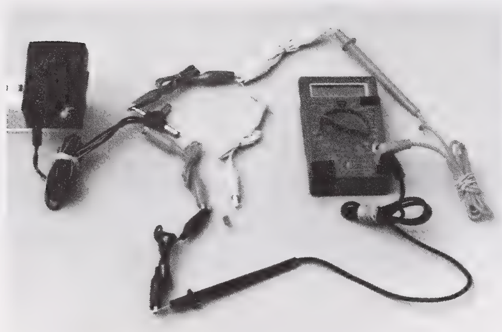
- Copy the following headings into your notebook. Be careful to leave enough space under each heading to record your answers. Complete the charts by recording the values for each LED. Completed data charts will be included in the Appendix for your reference.

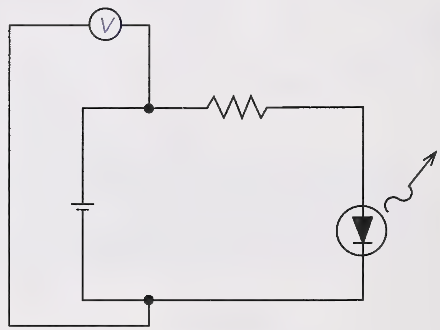
Red LED $\lambda = 6.3 \times 10^{-7}$ m	
V (Volts)	I $(\times 10^{-3}\ \text{A})$

Amber LED $\lambda = 5.9 \times 10^{-7}$ m	
V (Volts)	I $(\times 10^{-3}\ \text{A})$

Green LED $\lambda = 5.4 \times 10^{-7}$ m	
V (Volts)	I $(\times 10^{-3}\ \text{A})$

- Without turning on the low-voltage power supply, build the circuit shown in the following photograph and schematic diagram. Use the red LED.





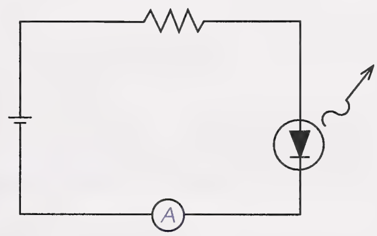
- Inspect the circuit to check that all the connections with the alligator clips are secure, the multimeter is properly set up, and the resistor is in series with the red LED.

- Adjust the power supply to provide an output of about 5 V and turn on the source to supply voltage to the circuit.

- The LED should be emitting light. If it is not, disconnect it and reconnect it in the reverse position.

- Determine the potential difference supplied to the entire circuit. Record this value on the data chart for the red LED.

- Without changing the setting on the power supply, disconnect the multimeter. Reset the dial on the meter and the position of the leads to measure current in mA. Reconnect the meter and measure the current flowing through the entire circuit shown in the following diagram. Record the current value beside the voltage value on the data chart for the red LED.



9. Repeat the previous two steps at least five more times, each time with a slightly higher potential difference on the power supply. **Do not** exceed 20 V. In each case record your values of potential difference and current side by side on the data chart for the red LED.

10. Repeat the entire procedure for the amber LED and the green LED. In each case record the collected data on the appropriate data chart.

Graphing

11. Plot the data of potential difference versus current for the red LED. Even though potential difference is actually the manipulated variable, plot it on the y-axis and current on the x-axis. This will make the analysis that follows easier.

    Use the standard graph paper with 1-cm squares. Be sure to leave sixteen squares on the horizontal axis and twenty squares on the vertical axis.

    Draw the best-fit straight line for your points very carefully. Extend the line until it intercepts the y-axis.

12. Repeat the previous question for the amber LED. Carefully plot the graph on a separate sheet of graph paper.

13. Repeat question 11 for the green LED. Carefully plot the graph on a separate sheet of graph paper.

14. Calculate the slope and determine the y-intercepts for each of the graphs. What do these slope values represent?

Check your answers by turning to the Appendix, Section 2: Activity 2.

Graphical Analysis

Given all the work you have just completed with the three graphs, you are probably wondering how this is going to help determine an experimental value for Planck's constant. You'll be glad to know that you're only one step away from determining **three** values for Planck's constant, one for each of the LED graphs. However, it is important to know why the calculation works before you start plugging numbers into your calculator. The following flow chart shows how the key ideas fit together.

The law of conservation of energy can be applied to this circuit.

$$\sum E_{before} = \sum E_{after}$$

$$E_{power\ supply} = E_{thermal} + E_{light}$$

Ignoring internal energies within the LED, the energies can be approximated as follows.

$$qV_{power\ supply} = q(IR) + \frac{hc}{\lambda}$$

Divide all terms by q.

$$V_{power\ supply} = RI + \frac{hc}{q\lambda}$$

This final equation approximates the relationship that you graphed for all three LEDs.

Since the goal is to determine a value for Planck's constant, it would be a good strategy to find out what part of the graph represents the term $\frac{hc}{q\lambda}$. This value can then be used to determine an experimental value for Planck's constant.

15. Explain what part of the graph represents the term $\frac{hc}{q\lambda}$.

Conclusions

16. Determine an experimental value for Planck's constant for each LED.

17. Find an average of the Planck's constant values that you obtained and use that value to determine a percent error for this investigation.

18. Evaluate the design of this experiment by referring to your values for Planck's constant and the percent error.

The photoelectric effect has many applications that you may encounter on a day-to-day basis. Figure 27-3 on page 557 and the Sociology Connection on page 561 outline some of these applications. Study these sections and answer the following questions.

19. How is the photoelectric effect used to help reduce energy costs?

20. How can the photoelectric effect be used to make buildings more accessible to people who are physically handicapped?

21. How does the photoelectric effect help run some types of calculators?

22. Many people think that the most relevant application of the photoelectric effect is vision itself. The photoreceptors in your eyes perform a function similar to that of a photovoltaic cell.

    a. Draw a simple flow chart to illustrate how the eyes use the photoelectric effect.

    b. Suggest a reason why ultraviolet light is dangerous if it is directed into your eyes for prolonged periods of time.

23. If vision is the most relevant application of the photon theory of light, photosynthesis in plants must surely be the most important. Assume that it takes approximately nine photons from the red part of the spectrum $(\lambda = 665\ \text{nm})$ to provide the energy to transform one molecule of carbon dioxide into a carbohydrate.

    a. Calculate the light energy needed to transform one carbon dioxide molecule into a carbohydrate.

b. The following simplified equation is one way to summarize the process of photosynthesis.

Light energy

$$6CO_2 + 12H_2O \rightarrow C_6H_{12}O_6 + 6H_2O + 6O_2$$

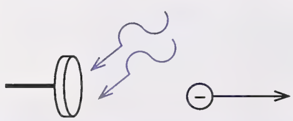
How much light energy is required for this process to work?

c. The pigment responsible for absorbing the light photons is chlorophyll, which is located in the chloroplasts of the photosynthetic cells. It is the chlorophyll that gives plants their green colour. Explain why it makes sense that photosynthetic plants make the most use of photons from the red and blue ends of the spectrum.

d. Plants use visible light because it is available as the most plentiful type of radiation that reaches the surface of Earth from the sun. Visible light is also used because the photons from this part of the spectrum have energy values that provide just the right amount of energy for energy transitions within the large organic molecules of living systems. Explain why ultraviolet photons and infrared photons are generally not suitable for photosynthesis.

Check your answers by turning to the Appendix, Section 2: Activity 2.

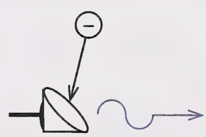
One application that is very similar to the photoelectric effect is the production of x-rays. In fact, as the following graphic indicates, x-ray production can be thought of as the photoelectric effect in reverse.



Photons strike a metal target.

The photons' energy is used to eject electrons.

$$hf = E_{k_{max}} + W$$



Electrons strike a metal target.

The electrons' energy is used to create x-ray photons.

$$E_k = hf_{max}$$

The photoelectric effect involves mainly visible light and ultraviolet photons. So in this case, the work done on the metal to liberate the electrons is a significant term. In the case of x-ray production, the energies are so much larger that only a small portion of the energy is lost to internal energy within the metal. The maximum frequency of the resulting x-rays occurs when all of the kinetic energy of the incident electron is used to create the x-ray photon.

24. Use the law of conservation of energy to derive the following equation.

Planck's constant

Voltage used to accelerate the electrons

$$\boxed{Vq = hf_{max}}$$

Maximum frequency of the x-ray photon

Charge on one electron

Many of the assumptions that Einstein used to state his theory of the photoelectric effect apply equally well to the production of x-rays. These assumptions are summarized in the following list:

- X-ray energy is concentrated in separate bundles called photons.
- The energy of each x-ray photon is described by the equation $E = hf$.
- The production of an x-ray photon by an electron is immediate.
- One x-ray photon is created by the collision of one electron.
- Energy is conserved.

25. Explain why increasing the current in the x-ray tube means that more x-rays will be produced.

26. Explain why increasing the voltage in the x-ray tube means that the frequency of the x-rays will also increase.

27. Electrons in a cathode-ray tube are accelerated by a potential difference of 7.0×10^{3} V. What is the maximum frequency of the x-rays that are produced?

28. The screen of your television contains lead to shield you from x-rays.

    a. If the picture tube accelerates electrons through 1.95×10^{4} V, calculate the minimum wavelength of the x-rays produced.

    b. The insides of a television can be a very dangerous environment for a technician attempting repair work. Explain some hazards, other than electrocution, which are faced by the technician.

29. An x-ray machine is designed to produce x-rays with a minimum wavelength of 7.5×10^{-10} m. What potential difference should be used to accelerate the electrons?

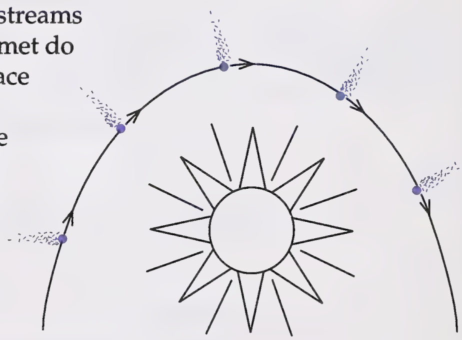
Check your answers by turning to the Appendix, Section 2: Activity 2.

In the first two activities of this section you have seen that the photon model of light provides new support for the idea that light is a particle. Yet the wave nature of light cannot be entirely discounted either because the energy of a photon is determined by its frequency, which is clearly a wave characteristic.

duality – the property of having two fundamentally different natures

The word **duality** is often used to describe the fact that light seems to have two natures that complement each other – a wave nature and a particle nature. In the next activity you will discover that the idea of duality actually has provided implications for both light and subatomic particles.

Activity 3: Wave-Particle Duality



Did you know that the tail of a comet always streams away from the sun? Why does the tail of a comet do this? It could not be air resistance because space is a vacuum and there is no air to resist the motion of the comet. Even if there was air, the tail would follow behind the comet.

Albert Einstein suggested a reason for this phenomenon that is based on the photon model of light. Einstein's proposal states that the sun constantly emits a huge number of photons that effectively create a photon wind that comes from the sun in all directions. The tiny particles that make up the tail of the comet have a pressure exerted on them by the momentum of the sun's photons.

Einstein's idea of photons having momentum takes the particle model of light a step further than was suggested by the photoelectric effect. But how can a photon have momentum if it has no mass? After all, isn't momentum the product of mass times velocity? Einstein solved this problem by suggesting that since mass and energy are really equivalent to each other, as given by the equation $E = mc^2$ (you'll learn more about this idea in the next module), a photon's energy can act as an equivalent substitute for its mass. The following flow chart sums this up.

$$p = mv$$

$$E = mc^2$$

For photons, the mass can be substituted by an equivalent amount of energy.

$$m = \frac{E}{c^2}$$

$$p = \left(\frac{E}{c^2}\right)v$$

Photons only have one speed in a vacuum – the speed of light. Therefore, $v = c$.

$$p = \left(\frac{E}{c^2}\right)c$$

Simplify.

Momentum of a photon → $p = \dfrac{E}{c}$ ← Energy of a photon; ← Speed of light: $c = 3.00 \times 10^8$ m/s

1. Derive an equation for the momentum of a photon in terms of the photon's frequency.
2. Derive an equation for the momentum of a photon in terms of the photon's wavelength.
3. Use your answers to the previous two questions to speculate on which parts of the electromagnetic spectrum would have photons with the greatest amount of momentum.

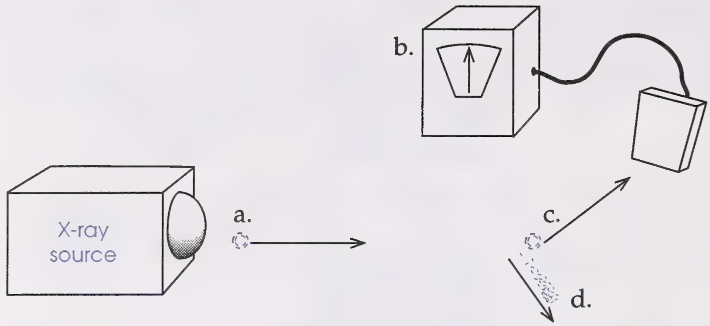
Check your answers by turning to the Appendix, Section 2: Activity 3.

The idea of photons having momentum was considered a bold notion. How could you possibly test this sort of idea? As you'll discover in the next video, Arthur Compton managed to prove experimentally that photons do have momentum.

The video series *Wave Particle Duality* contains a ten-minute program called *Photons*. Familiarize yourself with the following questions prior to watching the program. This will help you focus on the main ideas while you are viewing. You may have to periodically stop the tape in order to record your answers.

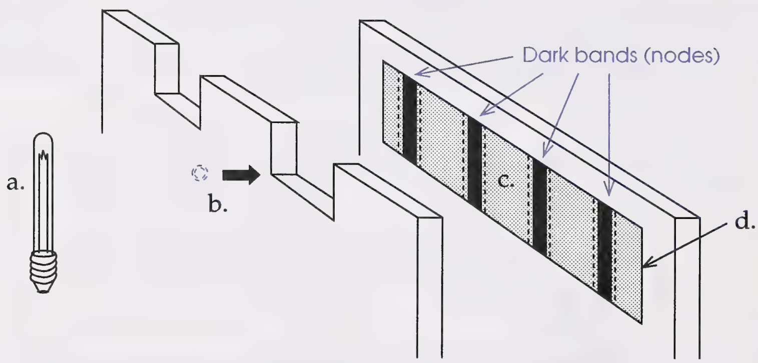
Compton effect – X-ray photons obey the laws of conservation of energy and momentum when they scatter off electrons.

4. The following diagram summarizes the **Compton effect**. The key components of Compton's apparatus have been labelled with letters. Describe each of the labelled parts in the diagram.



5. Refer to the previous diagram. Represent the results in a way that shows that momentum is conserved.

6. The following diagram illustrates Geoffrey Taylor's equipment with the interference pattern created by single photons. Describe each of the labelled parts in the diagram.



7. Refer to the diagram in the previous question. How many photons approached the slits at the time and how long did it take for the pattern to develop?

8. Explain why the wave model is still needed to explain Taylor's results.

9. Give one example of a type of electromagnetic wave that is more wave-like and one example that is more particle-like.

Stop the videotape at the end of the program.

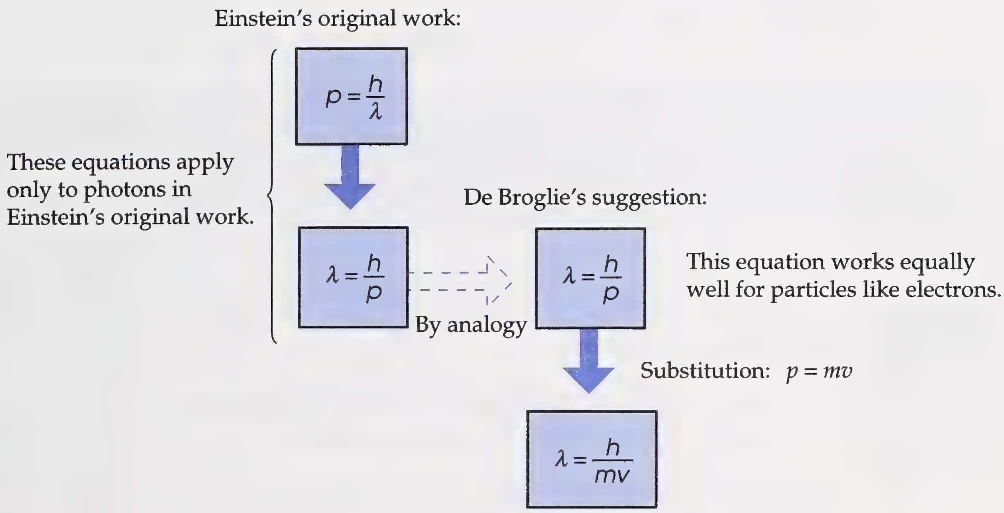
Check your answers by turning to the Appendix, Section 2: Activity 3.

The photon model for light and the electromagnetic model are both needed to provide a clear understanding of light. Rather than trying to decide if light is a particle or a wave, it is probably best to say that sometimes light behaves like a particle and sometimes it behaves like a wave, but it is inadequate to say that it is exclusively one or the other. This idea is sometimes referred to as **wave-particle duality**.

wave-particle duality – Photons and subatomic particles sometimes behave like particles and sometimes like waves.

If photons can act like particles sometimes and like waves other times, can the same be said about electrons? Electrons have particle properties such as rest mass, momentum, and charge, but do they also have wave properties?

These startling questions were first asked by Louis de Broglie. He sought an equation for the wavelength of electrons in Einstein's equation for the momentum of photons. This is shown in the following flow chart.



How could this novel idea possibly be tested? You'll find out whether de Broglie's ideas are valid in the next video program.

The video series *Wave Particle Duality* contains a ten-minute program called *Matter Waves*. Familiarize yourself with the following questions prior to watching the program. This will help you focus on the main ideas while you are viewing. You may have to periodically stop the tape in order to record your answers.

10. Geoffrey Taylor's experiment showed conclusively that single photons can produce an interference pattern that is predicted by the wave model. How can the bright lines of the interference pattern be interpreted in this scheme?

11. What circumstances must exist before a wave will not diffract around an obstacle?

12. Sketch a diagram to illustrate how x-ray diffraction can be observed.

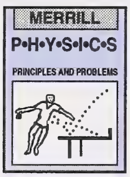
13. Sketch a diagram to illustrate how electron diffraction can be observed.

14. Copy the following headings into your notebook. Be careful to leave enough space under each heading to record your answers. Complete the chart in your notebook by concisely describing the differences between electrons and x-rays.

	X-ray Photons	Electrons
Speed		
Rest Mass		

Stop the tape when the program ends.

Check your answers by turning to the Appendix, Section 2: Activity 3.



You can learn more about the wave-particle duality by reading the last two paragraphs on pages 564 and pages 566 to 568 of the textbook. When you have finished reading, do the following questions.

15. Do questions 9 to 12, which are found in the lower right column of page 707 and the top left column of page 708 of your textbook.

16. Do Concept Review questions 2.1, 2.2, and 2.3 on page 569 of your textbook.

Check your answers by turning to the Appendix, Section 2: Activity 3.

The fact that electrons have wave properties has led to the development of the electron microscope. This machine can produce images with a resolution thousands of times greater than conventional light microscopes. If you've studied cells in previous science courses, you've likely seen very detailed images of the smaller parts of cells that were produced using an electron microscope.

The cover of this module shows John McCaffrey of the National Research Council of Canada with a transmission electron microscope. You will have a chance to learn more about another type called the scanning tunnelling electron microscope in one of the Enrichment activities for this section.

Follow-up Activities

If you had difficulties understanding the concepts in the activities, it is recommended that you do the Extra Help. If you had a clear understanding of the concepts, it is recommended that you do the Enrichment.

Extra Help

In this section you have seen how a series of experiments have advanced the photon model of light and have led to the idea of wave-particle duality. The following summary chart will enable you to concisely record the key ideas from this section.

Copy the following headings into your notebook. Be careful to leave enough space under each heading to record your answers. Complete the chart by adding the necessary descriptions under each heading.

How the Photon Model and Wave-Particle Duality Developed		
Name of Experiment or Apparatus	**How did this work advance the photon model of light or wave-particle duality?**	**New Equations that Developed from this Work**
Blackbody Radiation		
Photoelectric Effect		
Compton Effect		
Electron Diffraction		

Check your answers by turning to the Appendix, Section 2: Extra Help.

Enrichment

MERRILL P•H•Y•S•I•C•S PRINCIPLES AND PROBLEMS

Choose **one** of the following activities.

1. Light-Emitting Diodes

   Read pages 605 to 607 in your textbook if you would like to find out more about LEDs. The following questions will help you focus on the main ideas.

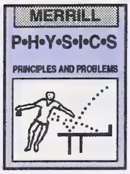
a. What combinations of elements in LEDs produce light?

b. How are diode lasers produced?

c. How can a reverse-biased pn-junction diode be used?

2. Scanning Tunnelling Microscope

An exciting application of the wave-particle duality applied to electrons is the scanning tunnelling microscope. You can find out more about this technology by reading the Physics and Technology section on page 590 of the textbook and by answering the question at the end of the reading.



Check your answers by turning to the Appendix, Section 2: Enrichment.

Conclusion

In this section you have seen that the quantum idea can lead to startling insights when it is applied to light. However, the photon combines characteristics of both particles and waves in a way that is often called the wave-particle duality. The duality can also be extended to particles such as electrons. It would appear that in the subatomic world, the large-scale categories of particles and waves are too limiting to describe the observed phenomena.

Assignment Booklet

ASSIGNMENT

Turn to your Assignment Booklet and do the assignment for Section 2.

MODULE SUMMARY

You can see why this module began by explaining revolution in science and the thirty years that rocked physics. At the heart of modern physics is the idea that many quantities on the atomic and subatomic scales come in bundles called quanta. This seems to be the way that nature is designed. Charge is quantized and energy from the electromagnetic spectrum is also quantized. Tied up in both of these quantum models is the notion of wave-particle duality. If you find this all quite abstract and remote, try to keep applications like vision and photosynthesis in mind. You will explore other applications of quantum ideas in Module 9.

Appendix

Glossary

Suggested Answers

Glossary

blackbody radiation: radiation from a hot and luminous body that absorbs all the radiation that falls on it

Compton effect: X-ray photons obey the laws of conservation of energy and momentum when they scatter off electrons.

duality: the property of having two fundamentally different natures

electron volt: energy that an electron acquires when it is accelerated by 1 V; $1\ \text{eV} = 1.60 \times 10^{-19}\ \text{J}$

LED: abbreviated term for light-emitting diode

light-emitting diode: a semiconductor device that can emit light when current passes in the right direction

mass spectrometer: a device used to determine the masses of atoms or molecules

photoelectric effect: Electrons are liberated from a surface due to the presence of electromagnetic radiation.

photoelectrons: electrons that are emitted from a surface due to the photoelectric effect

photon: a quantum of electromagnetic radiation

Planck's constant: ratio of the energy of a photon to its frequency

$h = 6.63 \times 10^{-34}\ \text{J} \bullet \text{s}$

quanta: plural form of quantum

quantized: made up of multiples of some fundamental quantum value

quantum: the smallest value that can exist for a quantity. All other values are multiples of this fixed amount.

stopping voltage: potential difference that can stop even the most energetic photoelectrons

threshold frequency: the minimum frequency of light which gives rise to the photoelectric effect

wave-particle duality: Photons and subatomic particles sometimes behave like particles and sometimes behave like waves.

work function: minimum energy required to free electrons from a metal surface

Suggested Answers

Section 1: Activity 1

1. a. The atomism concept states that matter consists of particles that cannot be split because they are ultimately the smallest particles possible.

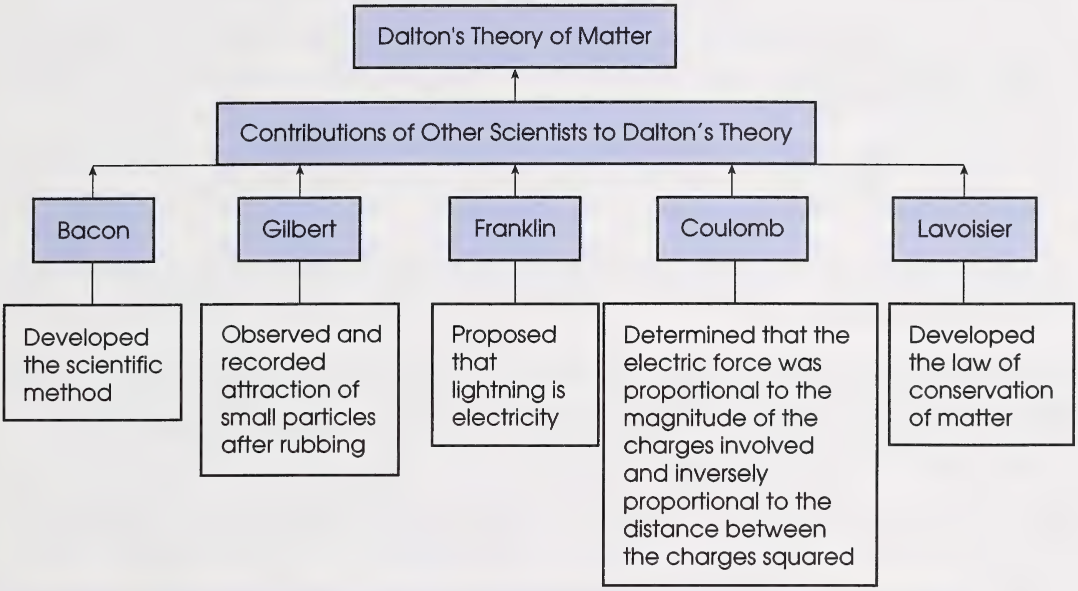
   b. Democritus developed this concept.

   c. Matter consists of atoms and the void.

   d. The concept was developed using logic.

2. a. Transmutation refers to the changing of common metals into silver and gold.
   b. Alchemists developed these ideas.
   c. Each type of matter was composed of a single formless substance.
   d. Observation and experimentation was used to develop these ideas.

3.



4.

	Early Greek Model	Dalton's Model
All matter is made up of atoms.	agree	agree
Atoms have motion.	agree	agree
Atoms are indivisible.	agree	agree
Things differ because of atoms.	? no ideas	agree

5. Faraday's work with electrolysis led him to the conclusion that atoms of compounds are held together by electricity.

6. They were called cathode rays because they seemed to originate at the cathode..

7. The shape of the shadow is identical to the shape of the cross itself. The only way this could occur is if the cathode rays travelled in straight lines.

8. The increase in temperature indicates that the cathode rays transfer energy.

9. Crookes thought that the cathode rays were negatively charged particles. He could not be sure of this because he was not able to see if they were deflected by electric fields.

10. In step 1 the cathode-ray particles are accelerated from the cathode towards the anode. The particles pass through the circular plates and travel undeflected towards the opposite end of the tube.

    In step 2 the particles are deflected up towards the positive plate by the upward electric force. The particles would follow a projectile path shaped like a parabola. Once the particles pass through the space between the plates, they travel in a straight line to the upper end of the tube.

    In step 3 the particles are deflected downward due to the presence of a magnetic force caused by the magnetic field created by the solenoid. The resulting motion produces a circular path. Once the particles pass through the solenoid, they continue to move in a straight line towards the bottom of the tube.

    In step 4 the upward force of the electric field was cancelled by the downward force of the magnetic field. Since the net force on the cathode particles was zero in this step, the cathode particles travelled undeflected to the opposite end of the tube.

11. In step 3 the cathode particles moved in a path that is a portion of a circle as they travelled in the magnetic field created by the solenoid. The variable *r* shows the radius of the path of the cathode-ray particle. The particle did not move in a full circle because the magnetic field was only intense enough and/or large enough to cause the motion to be in a part of a circle.

12. Thomson was eventually able to calculate the charge-to-mass ratio for cathode-ray particles with this apparatus.

13. No matter what substance the cathode was made from, the cathode-ray particles had the same charge-to-mass ratio.

14. Cathode-ray particles were eventually called electrons.

15. Figure 26-1(b) does not show the solenoids that created the magnetic fields.

16. These forces are equal in magnitude since the beam of cathode rays travels undeflected.

$$F_m = F_e \;\xrightarrow{\text{Substitute.}}\; qvB_\perp = q\left|\vec{E}\right| \;\xrightarrow{\text{Cancel the charge from both sides.}}\; vB_\perp = \left|\vec{E}\right| \;\xrightarrow{\text{Rearrange.}}\; v = \frac{\left|\vec{E}\right|}{B_\perp}$$

17. The magnetic force provides the centripetal force necessary for circular motion.

$$F_m = F_c \;\xrightarrow{\text{Substitute.}}\; qvB_\perp = \frac{mv^2}{r} \;\xrightarrow{\text{Rearrange.}}\; \frac{q}{m} = \frac{v^2}{rvB_\perp} \;\xrightarrow{\text{Simplify.}}\; \frac{q}{m} = \frac{v}{rB_\perp}$$

18. a. $v = 5.50 \times 10^6 \text{ m/s}$

$B_\perp = 6.38 \times 10^{-4} \text{ T}$

$r = 49 \text{ mm} = 4.9 \times 10^{-2} \text{ m}$ } This is a measurement from the true-size diagram.

$$F_m = F_c$$

$$qvB_\perp = \frac{mv^2}{r}$$

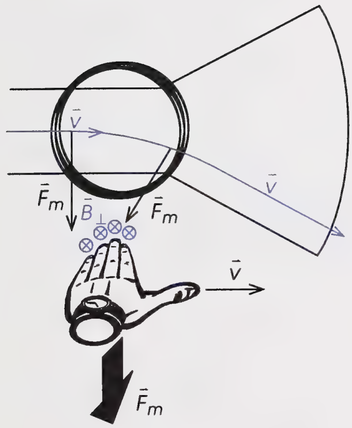
$$\frac{q}{m} = \frac{v}{rB_\perp}$$

$$= \frac{\left(5.50 \times 10^6 \text{ m/s}\right)}{\left(4.9 \times 10^{-2} \text{ m}\right)\left(6.38 \times 10^{-4} \text{ T}\right)}$$

$$= 1.76 \times 10^{11} \text{ C/kg}$$

$$= 1.8 \times 10^{11} \text{ C/kg}$$

b.



The magnetic force is directed down. The left-hand rule for force indicates that the magnetic field is directed straight into the page.

19. $d = 1.00 \text{ cm} = 1.00 \times 10^{-2} \text{ m}$

$V = 200 \text{ V}$

$B_\perp = 1.01 \times 10^{-3} \text{ T}$

$v = ?$

$$F_m = F_e$$

$$qvB_\perp = q\left|\vec{E}\right|$$

$$v = \frac{\left|\vec{E}\right|}{B_\perp}$$

$$= \frac{\left(\frac{V}{d}\right)}{B_\perp}$$

$$= \frac{\left(\frac{200 \text{ V}}{1.00 \times 10^{-2} \text{ m}}\right)}{1.01 \times 10^{-3} \text{ T}}$$

$$= 1.98 \times 10^7 \text{ m/s}$$

You can now use the speed value to calculate the charge-to-mass ratio when the electrons move through the magnetic field alone.

$r = 0.114 \text{ m}$

$B_\perp = 1.01 \times 10^{-3} \text{ T}$

$v = \frac{\left|\vec{E}\right|}{B_\perp}$

$\frac{q}{m} = ?$

$$F_m = F_c$$

$$qvB_\perp = \frac{mv^2}{r}$$

$$\frac{q}{m} = \frac{v}{rB_\perp}$$

$$= \frac{\left(1.98 \times 10^7 \text{ m/s}\right)}{(0.114 \text{ m})\left(1.01 \times 10^{-3} \text{ T}\right)}$$

$$= 1.72 \times 10^{11} \text{ C/kg}$$

20. Textbook question 4:

Step 1: Calculate the speed of the electrons.

Step 2: Calculate the radius of the path.

$B_\perp = 6.0\times10^{-2}\ \text{T}$

$|\vec{E}| = 3.0\times10^{3}\ \text{N/C}$

$v = ?$

$r = ?$

$$F_m = F_e$$
$$qvB_\perp = q|\vec{E}|$$
$$v = \frac{|\vec{E}|}{B_\perp}$$
$$= \frac{3.0\times10^{3}\ \text{N/C}}{6.0\times10^{-2}\ \text{T}}$$
$$= 5.0\times10^{4}\ \text{m/s}$$

$$F_m = F_c$$
$$qvB_\perp = \frac{mv^2}{r}$$
$$r = \frac{mv^2}{qvB_\perp}$$
$$= \frac{mv}{qB_\perp}$$
$$= \frac{(9.11\times10^{-31}\ \text{kg})(5.0\times10^{4}\ \text{m/s})}{(1.60\times10^{-19}\ \text{C})(6.0\times10^{-2}\ \text{T})}$$
$$= 4.7\times10^{-6}\ \text{m}$$

21. Objects with larger mass have more inertia and it is more difficult to change their path of travel. An alternative explanation is shown in the solution to the previous question where the equation for the radius is given as $r = \frac{mv}{qB_\perp}$. Clearly, a larger value for mass will create a larger value for radius.

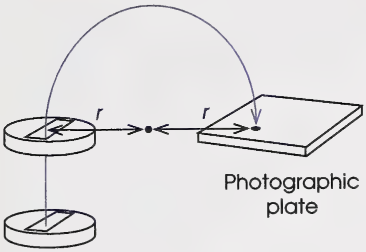
22.

$$F_m = F_c$$
$$qvB_\perp = \frac{mv^2}{r}$$
$$r = \frac{mv^{\cancel{2}}}{q\cancel{v}B_\perp}$$
$$= \frac{mv}{qB_\perp}$$
$$r^2 = \frac{m^2v^2}{q^2B_\perp^{\ 2}}$$
$$= \frac{m^{\cancel{2}}\left(\frac{2V\cancel{q}}{\cancel{m}}\right)}{q^{\cancel{2}}B_\perp^{\ 2}}$$
$$= \frac{2mV}{qB_\perp^{\ 2}}$$
$$\frac{q}{m} = \frac{2V}{B_\perp^{\ 2}r^2}$$

$$E_{\textit{power supply}} = E_k$$
$$Vq = \frac{1}{2}mv^2$$
$$v^2 = \frac{2Vq}{m}$$

Substitute.

23.



The particles move through a semicircular path. The distance between the slot and the mark on the photographic plate is the diameter of a circle, $2r$.

24. A mass spectrometer can be used to detect trace amounts of dangerous materials that may be present in waste that is passed on to the environment.

25. Textbook question 5.a.:

$B_\perp = 1.5 \times 10^{-3}\ \text{T}$

$|\vec{E}| = 6.0 \times 10^{2}\ \text{V/m}$

$v = ?$

$$\begin{aligned} F_m &= F_e \\ \cancel{q}vB_\perp &= \cancel{q}|\vec{E}| \\ v &= \frac{|\vec{E}|}{B_\perp} \\ &= \frac{6.0 \times 10^{2}\ \text{V/m}}{1.5 \times 10^{-3}\ \text{T}} \\ &= 4.0 \times 10^{5}\ \text{m/s} \end{aligned}$$

Textbook question 5.b.:

$q = 1.60 \times 10^{-19}\ \text{C}$

$B_\perp = 0.18\ \text{T}$

$r = 0.165\ \text{m}$

$v = 4.0 \times 10^{5}\ \text{m/s}$

$m = ?$

$$\begin{aligned} F_m &= F_c \\ qvB_\perp &= \frac{mv^2}{r} \\ m &= \frac{q\cancel{v}B_\perp r}{v^{\cancel{2}}} \\ &= \frac{qB_\perp r}{v} \\ &= \frac{(1.60 \times 10^{-19}\ \text{C})(0.18\ \text{T})(0.165\ \text{m})}{4.0 \times 10^{5}\ \text{m/s}} \\ &= 1.2 \times 10^{-26}\ \text{kg} \end{aligned}$$

Textbook question 8:

Original neon isotope:

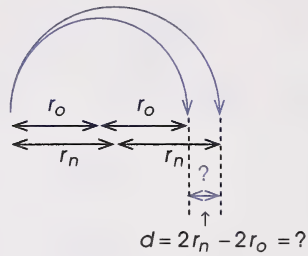
$m_o = 20$ units

$r_o = 0.053$ m

New neon isotope:

$m_n = 22$ units

$r_n = ?$



The technique for solving this problem is to realize that since all the other variables are kept constant, a ratio and proportion method can be used.

Original neon isotope:

$$\frac{q}{m_o} = \frac{2V}{B_\perp^2 r_o^2}$$

$$r_o^2 = \frac{2Vm_o}{B_\perp^2 q}$$

New neon isotope:

$$\frac{q}{m_n} = \frac{2V}{B_\perp^2 r_n^2}$$

$$r_n^2 = \frac{2Vm_n}{B_\perp^2 q}$$

$$\frac{r_n^2}{r_o^2} = \frac{\left(\frac{\cancel{2V}m_n}{\cancel{B_\perp^2 q}}\right)}{\left(\frac{\cancel{2V}m_o}{\cancel{B_\perp^2 q}}\right)}$$

$$\frac{r_n^2}{r_o^2} = \frac{m_n}{m_o}$$

$$r_n^2 = \frac{m_n}{m_o} r_o^2$$

$$= \frac{(22 \text{ units})}{(20 \text{ units})}(0.053 \text{ m})^2$$

$$r_n^2 = 0.003\,089\,9 \text{ m}^2$$

$$r_n = 0.0556 \text{ m}$$

$$= 0.056 \text{ m}$$

The distance between the marks should equal $2r_n - 2r_o$.

$$\begin{aligned} d &= 2r_n - 2r_o \\ &= 2(0.0556 \text{ m}) - 2(0.053 \text{ m}) \\ &= 0.0052 \text{ m} \\ &= 0.005 \text{ m} \end{aligned}$$

The marks would be separated by 5 mm.

26. Textbook question 9.a.:

$m = 6.6 \times 10^{-27}$ kg

$q = +3.2 \times 10^{-19}$ C

$B_{\perp} = 2.0$ T

$r = 0.15$ m

$v = ?$

$$\begin{aligned} F_m &= F_c \\ q\cancel{v}B &= \frac{mv^{\cancel{2}}}{r} \\ v &= \frac{qBr}{m} \\ &= \frac{(3.2 \times 10^{-19} \text{ C})(2.0 \text{ T})(0.15 \text{ m})}{6.6 \times 10^{-27} \text{ kg}} \\ &= 1.45 \times 10^{7} \text{ m/s} \\ &= 1.5 \times 10^{7} \text{ m/s} \end{aligned}$$

Textbook question 9.b.:

$E_k = ?$

$v = 1.45 \times 10^{7}$ m/s

$m = 6.6 \times 10^{-27}$ kg

$$\begin{aligned} E_k &= \frac{1}{2}mv^2 \\ &= \frac{1}{2}(6.6 \times 10^{-27} \text{ kg})(1.45 \times 10^{7} \text{ m/s})^2 \\ &= 6.94 \times 10^{-13} \text{ J} \\ &= 6.9 \times 10^{-13} \text{ J} \end{aligned}$$

Note that an energy value of 7.0×10^{-13} J is acceptable if you use $1.45\overline{45} \times 10^{7}$ m/s for speed.

Textbook question 9.c.:

$V = ?$

$q = 3.2 \times 10^{-19}$ C

$\Delta E = E_k = 6.94 \times 10^{-13}$ J (assuming the particle starts from rest)

$$\begin{aligned} V &= \frac{\Delta E}{q} \\ &= \frac{6.94 \times 10^{-13} \text{ J}}{3.2 \times 10^{-19} \text{ C}} \\ &= 2.17 \times 10^{6} \text{ V} \\ &= 2.2 \times 10^{6} \text{ V} \end{aligned}$$

Section 1: Activity 2

1. The downward arrow in step 1 represents the force of gravity.

2. The force of air resistance will play a significant role because the mass of the droplets is so small.

3. The upward arrow in step 2 represents the electrostatic force acting on the oil droplets.

4. The oil drops must have a negative charge because they are being repelled upward by the negative plate.

5. The small horizontal arrows in step 3 represent x-rays that are ionizing the air in the region between the plates.

6. The x-rays ionize the air between the plates. This means that free electrons are available to attach to the oil droplets. This means that the electric field between the plates can exert a larger force on the droplets.

7. Millikan was able to measure the smallest rate of change in the charge of one oil droplet. He decided that this charge must be the charge on one electron.

8. Thomson used Millikan's result to create a model of the atom in which most of the mass of the atom was concentrated in positive matter. The analogy was made that electrons were like raisins in the dough of a raisin bun atom.

9.

Motion of Oil Droplet Between the Plates	Is $\vec{F}_g$ or $\vec{F}_e$ larger?	What is the direction of the net force?
Accelerating Down	$\vec{F}_g$ is larger.	The direction of the net force is down, according to Newton's second law.
Suspended (at rest)	The two forces are equal in magnitude.	The net force is zero since the forces are balanced. This is in accordance with Newton's first law.
Accelerating Up	$\vec{F}_e$ is larger.	The direction of the net force is up, according to Newton's second law.
Uniform Motion Up or Down	The two forces are equal in magnitude.	The net force is zero. According to Newton's first law, objects maintain their velocity when the forces are balanced.

10. Millikan used a complex equation to calculate the mass from the terminal velocity of the drop.

11. No, this charge is smaller in magnitude than 1.60×10^{-19} C. Millikan found that a magnitude of 1.60×10^{-19} C is the smallest possible charge and that all other charges are multiples of this value.

12. The following data is typical of the data that you might obtain. Your values will be different, but the analysis that follows will work in any case.

Total Mass of an Unknown Number of Ball Bearings						
Trial	1	2	3	4	5	6
Mass (g)	151	250	449	76	474	326

13. Millikan found the smallest charge by finding the smallest difference between all the measured charges. All other values were a multiple of this smallest value.

14. By finding the smallest mass difference, you are finding the mass of one ball bearing. All other values should be multiples of this mass.

15. You are assuming that you have made enough measurements to have the smallest mass.

16. Order the masses from smallest to largest and find the smallest difference in the values.

Individual Masses (g)	Differences in the Masses (g)	Patterns in the Multiple Values (g)
76		
	75	$75 \div 3 = 25$
151		
	99	$99 \div 4 = 24.75$
250		
	76	$76 \div 3 = 25.\overline{3}$
326		
	123	$123 \div 5 = 24.6$
449		
	25	$25 \div 1 = 25$
474		

In the case of this sample data, the smallest mass was 25 g. Close examination of the other values reveals that they are all close to being multiples of 25 g. The best estimate of the mass of one ball can be found by averaging the five values (from either the differences or the multiples).

$$
\begin{aligned}
m &= \frac{\sum \Delta m}{5} \\
&= \frac{(124.68\overline{3}\ \text{g})}{5} \\
&= 24.9\ \text{g} \\
&= 25\ \text{g}
\end{aligned}
$$

Since this process is based on using the differences which are to two significant digits, the answer should also be stated to two significant digits.

17. The unit mass could not be larger because that value could not account for the smallest mass value. For example, if the unit mass was 50 g, how could 25 g occur? The mass could be smaller because you are assuming one ball bearing difference. For these results the smaller masses could be 5 g since the smallest value of 25 g could be due to five objects instead of one.

18. $\frac{V}{d}q = mg$

$$q = \frac{mgd}{V}$$

19. Textbook question 9.a.:

The forces acting on the oil drop are the force of gravity and the force of air resistance.

Textbook question 9.b.:

According to Newton's first law of motion, if the oil drop is falling with a constant speed, the forces acting on it are balanced.

Textbook question 10.a.:

$F_g = 1.9 \times 10^{-15}$ N

$|\vec{E}| = 6.0 \times 10^3$ N/C

$q = ?$

$$\begin{aligned}
\vec{F}_{net} &= \vec{F}_e + \vec{F}_g = 0 \\
\left|\vec{F}_e\right|_{up} + \left|\vec{F}_g\right|_{down} &= 0 \\
\left|\vec{F}_e\right| + -\left|\vec{F}_g\right| &= 0 \\
\left|\vec{F}_e\right| &= \left|\vec{F}_g\right| \\
\left|\vec{E}\right|q &= \left|\vec{F}_g\right| \\
q &= \frac{\left|\vec{F}_g\right|}{\left|\vec{E}\right|} \\
&= \frac{1.9 \times 10^{-15}\ \text{N}}{6.0 \times 10^{3}\ \text{N/C}} \\
&= 3.2 \times 10^{-19}\ \text{C}
\end{aligned}$$

Textbook question 10.b.:

n electrons $= 3.2 \times 10^{-19}$ C

1 electron $= 1.60 \times 10^{-19}$ C

$$\begin{aligned}
\frac{1\ \text{electron}}{1.60 \times 10^{-19}\ \text{C}} &= \frac{n}{3.2 \times 10^{-19}\ \text{C}} \\
n &= \frac{(1\ \text{electron})\left(3.2 \times 10^{-19}\ \text{C}\right)}{1.60 \times 10^{-19}\ \text{C}} \\
&= 2\ \text{electrons}
\end{aligned}$$

20. $$ma = q\left(\frac{V}{d}\right) - mg$$

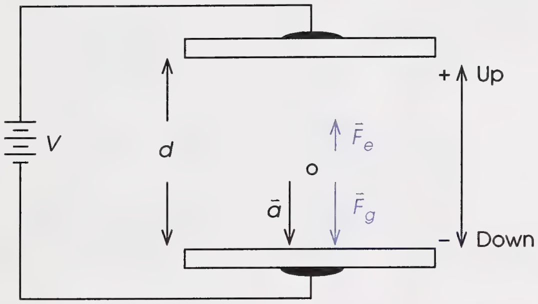
$$q\left(\frac{V}{d}\right) = ma + mg$$

$$q = \left(ma + mg\right)\frac{d}{V}$$

21. $$q = \frac{\left[\left(5.00\times10^{-16}\ \text{kg}\right)\left(2.20\ \text{m/s}^2\right)+\left(5.00\times10^{-16}\ \text{kg}\right)\left(9.81\ \text{m/s}^2\right)\right]\left(3.00\times10^{-2}\ \text{m}\right)}{9.00\ \text{V}}$$

$$= 2.00\times10^{-17}\ \text{C}$$

22. a.



$m = 6.30\times10^{-16}\ \text{kg}$

$V = 26.19\ \text{V}$

$d = 75.5\ \text{mm} = 7.55\times10^{-2}\ \text{m}$

$\vec{a} = -1.00\ \text{m/s}^2$

$\vec{g} = -9.81\ \text{m/s}^2$

$q = ?$

b. $$\vec{F}_{net} = \vec{F}_e + \vec{F}_g$$

$$\left|\vec{F}_{net}\right|_{down} = \left|\vec{F}_e\right|_{up} + \left|\vec{F}_g\right|_{down}$$

$$-\left|\vec{F}_{net}\right| = \left|\vec{F}_e\right| + -\left|\vec{F}_g\right|$$

$$-ma = q\left|\vec{E}\right| - mg$$

$$q\left|\vec{E}\right| = mg - ma$$

$$q\left(\frac{V}{d}\right) = m\left(g - a\right)$$

$$q = m\left(g - a\right)\frac{d}{V}$$

$$= \frac{\left(6.30\times10^{-16}\ \text{kg}\right)\left(9.81\ \text{m/s}^2 - 1.00\ \text{m/s}^2\right)\left(7.55\times10^{-2}\ \text{m}\right)}{26.19\ \text{V}}$$

$$= 1.60\times10^{-17}\ \text{C}$$

Note that the initial three statements about the forces dealt with the direction of the vectors so that only the magnitudes of the acceleration needed to be substituted. Also note that the sign of the charge is not given by the calculation since the equations deal only with the magnitudes of charges.

c. $n \text{ electrons} = 1.60 \times 10^{-17}\ \text{C}$

$1 \text{ electron} = 1.60 \times 10^{-19}\ \text{C}$

$$\frac{1 \text{ electron}}{1.60 \times 10^{-19}\ \text{C}} = \frac{n}{1.60 \times 10^{-17}\ \text{C}}$$

$$n = \frac{(1 \text{ electron})(1.60 \times 10^{-17}\ \text{C})}{1.60 \times 10^{-19}\ \text{C}}$$

$$= 100 \text{ electrons}$$

23. $\frac{q}{m} = 1.76 \times 10^{11}\ \text{C/kg}$

$q = 1.60 \times 10^{-19}\ \text{C}$

$m = ?$

$$\frac{q}{m} = 1.76 \times 10^{11}\ \text{C/kg}$$

$$m = \frac{q}{1.76 \times 10^{11}\ \text{C/kg}}$$

$$= \frac{1.60 \times 10^{-19}\ \text{C}}{1.76 \times 10^{11}\ \text{C/kg}}$$

$$= 9.09 \times 10^{-31}\ \text{kg}$$

The Physics 30 data sheets give a value of $9.11 \times 10^{-31}\ \text{kg}$. The difference in the two values is due to the fact that the rounded off value of the charge and charge-to-mass ratio were used.

24. $\frac{q}{m} = \frac{(1.76 \times 10^{11}\ \text{C/kg})}{1836}$

$= 9.586 \times 10^{7}\ \text{C/kg}$

$= 9.59 \times 10^{7}\ \text{C/kg}$

$q = +1.60 \times 10^{-19}\ \text{C}$

$m = ?$

$$\frac{q}{m} = 9.586 \times 10^{7}\ \text{C/kg}$$

$$m = \frac{q}{9.586 \times 10^{7}\ \text{C/kg}}$$

$$= \frac{1.60 \times 10^{-19}\ \text{C}}{9.586 \times 10^{7}\ \text{C/kg}}$$

$$= 1.67 \times 10^{-27}\ \text{kg}$$

The Physics 30 data sheets give the same value.

25. The quantum for the element iron is the smallest piece of iron that can exist. This is a single iron atom.

Section 1: Follow-up Activities

Extra Help

Name of Experiment or Apparatus	Description of What is Happening to the Charged Particle	Related Force Equations
Thomson's Experiment	Particles pass undeflected through a region of intense magnetic and electric fields.	$F_e = F_m$ $q\lvert\vec{E}\rvert = qvB_\perp$
Thomson's Experiment or Mass Spectormeter	The charged particle is forced to move in a circle. The magnetic force is providing the centripetal force necessary for circular motion.	$F_m = F_c$ $qvB = \frac{mv^2}{r}$
Millikan's Oil Drop Experiment	In this case the forces on the charged particle are balanced and the particle is suspended.	$\vec{F}_{net} = \vec{F}_e + \vec{F}_g = 0$ $\lvert\vec{F}_{net}\rvert = q\lvert\vec{E}\rvert - mg = 0$ $q\left(\frac{V}{d}\right) = mg$
Millikan's Oil Drop Experiment	The forces on the charged particle are not balanced, so a net force causes the particle to accelerate.	$\vec{F}_{net} = \vec{F}_e + \vec{F}_g \neq 0$ $\lvert\vec{F}_{net}\rvert = \lvert\vec{F}_e\rvert + \lvert\vec{F}_g\rvert$ $ma = q\lvert\vec{E}\rvert - mg$

Enrichment

1. The sample data and answers to questions for this investigation can be found in the teacher's version of the Laboratory Manual.

2. a. Photocopies feel warm when they first come out of the machine because the paper must be heated to melt the plastic beads that are attached to the charged areas of the drum. When the beads melt, the carbon grains that coat the beads become attached to the paper.

   b. Photocopies often stick together when they first leave the machine because they have become charged by the drum and other parts of the machine. The heating of the interior parts tends to dry out the inside of the machine and the paper, making the paper more prone to holding a static charge. For the pages to stick together, one side of each piece of paper would have to have one charge, while the other side would have to have the opposite charge induced.

c. The drum needs to be coated with a semiconductor so that it will hold the charge. If a conducting material was used, the charge would flow immediately to the conducting parts of the drum, and so there would be no charge left to attract the carbon-coated beads.

Section 2: Activity 1

1. No, red hot does not indicate the highest temperature possible. White hot indicates the highest temperature possible.

2. As the temperature of an object increases, the predominant radiation emitted shifts from infrared (which is invisible), to red, to orange, and then to yellow. Any increase in temperature beyond this point causes a greater proportion of the higher frequency green and blue light to be emitted, which blends with the other colours to produce an intense white light.

3. The surface of the sun looks like an intense white light when viewed from space. It is the scattering of the sun's light by Earth's atmosphere, which in effect takes some of the blue away. This gives the sun its yellow colour. The colour of an object, as indicated by the graph in Figure 27-1, is not determined by the peak of the curve, but rather considers the whole area under the curve.

4. A quantum of violet light would have more energy because the frequency of this light is higher.

5. Less energy needs to be brought together to form a quantum of red light than a quantum of violet light. An object would be more likely to emit the energy as a red photon than to delay the process and gather more energy to create a violet photon.

6. Yes, the answer to the previous question indicates the same thing that the graph does. There is a higher probability that an emitted photon will come from the red end of the spectrum.

7. This equation relates to the energy of vibration of atoms.

A whole number: $n = 0, 1, 2, 3, \ldots$

Planck's constant

Energy of vibration of atoms → $\boxed{E = nhf}$ ← Frequency of vibration of the atom

According to Planck's proposal, atoms can only have certain vibrational energies, as given by this equation. The light emitted by a hot body corresponds to a change in the atom's vibrational energy.

8. To say that energy is quantized means that energy can only occur in multiples of some fundamental value. In this case, all energies are multiples of hf, where the integer n indicates which particular multiple is formed.

9. a. This is the cathode that is coated with potassium.

   b. These are electrons that were emitted by the potassium atoms on the cathode. Since the emission was caused by light, the electrons are called photoelectrons.

c. This is the source of potential difference that keeps the cathode negative and the anode positive.

10. a. If red light was used, no electrons would be shown because no electrons are emitted by potassium when red light shines on it.

    b. No, the brightness of the light would not change the result.

    c. If the blue light was made more intense, more rays of blue light would be drawn and more photoelectrons would be added to show an increase in the current.

    d. If violet light was used, the emitted photoelectrons would be emitted with more energy. Perhaps this added energy could be indicated with longer velocity vectors to help convey the idea of increased kinetic energy.

11. A quantum of red light energy has a frequency that is low. Therefore its energy is too small to liberate electrons from the potassium. On the other hand, a quantum of blue light energy has a higher frequency and therefore a higher energy. A quantum of blue light does have enough energy to free an electron from the potassium.

12. If a higher frequency of light is used, the individual bundles of light energy will be able to free an electron from the potassium atoms and there will be additional energy available to give the photoelectrons increased kinetic energy as they travel to the anode.

13. If the light is made more intense (bright), more photons will strike the metal surface. This means that more electrons can be liberated from individual atoms and therefore the photoelectric current will increase.

14. The name given to the bundles of light energy is photons.

15. The electrons are called photoelectrons because they are emitted by light shining on atoms. These particles are identical to those studied by Thomson and Millikan. The only difference is that these are created by light striking a metal surface.

16. The threshold frequency is the minimum frequency of light which gives rise to the photoelectric effect.

17. The type of metal that is used to coat the cathode determines the threshold frequency. The reason for this is that each metal requires a specific amount of work to be done to free an electron from its atoms.

18. Blue light represented the threshold frequency in the video program.

19. Einstein made the following assumptions in explaining the photoelectric effect:

    - Light energy is quantized in bundles called photons.
    - The energy of each photon is given by $E = hf$.
    - The photoelectric effect is immediate.
    - One photon can liberate exactly one electron.
    - Energy is conserved.

20. This derivation begins with the law of conservation of energy.

$$\sum E_{input} = \sum E_{output}$$

Energy of the emitted photoelectrons

Energy of the incident light photon → $E_{light} = E_k + W$ ← Work done to liberate the photoelectrons

Substitute.

$$hf = E_k + hf_o$$

Rearrange.

$$E_k = hf - hf_o$$

21. The stopping potential, or stopping voltage, is the potential difference that supplies exactly the right amount of energy to turn around or stop even the most energetic photoelectrons.

22. An electron volt is an energy unit used primarily with atomic systems $\left(1\ \text{eV} = 1.60 \times 10^{-19}\ \text{J}\right)$. This energy is transferred when one electron is accelerated through one volt.

23. Textbook question 1:

$V_{stop} = 3.2\ \text{V}$

$q = 1.60 \times 10^{-19}\ \text{C}$

$E_{k_{max}} = ?$

$$\begin{aligned} E_{k_{max}} &= qV_{stop} \\ &= \left(1.60 \times 10^{-19}\ \text{C}\right)\left(3.2\ \text{J/C}\right) \\ &= 5.12 \times 10^{-19}\ \text{J} \\ &= 5.1 \times 10^{-19}\ \text{J} \end{aligned}$$

The equation for stopping voltage can be found in the Physics 30 data sheets.

Textbook question 2:

$V_{stop} = 5.7\ \text{V}$

$q = 1\ \text{e}$

$E_{k_{max}} = ?$

$$\begin{aligned} E_{k_{max}} &= qV_{stop} \\ &= (1\ \text{e})(5.7\ \text{V}) \\ &= 5.7\ \text{eV} \end{aligned}$$

The elementary charge, e, is used as the value for the charge of one electron to give units of electron volts.

24. The slope of the graph should correspond to Planck's constant.

25. Your answer to this question may differ slightly if you chose different data points.

$$(x_1, y_1) = \left(6.0\times10^{14}\ \text{Hz},\ 0.6\overline{6}\ \text{eV}\right)$$
$$(x_2, y_2) = \left(11.5\times10^{14}\ \text{Hz},\ 3.0\ \text{eV}\right)$$

$$\begin{aligned}\text{slope} &= \frac{\text{rise}}{\text{run}}\\ &= \frac{\left(3.0\ \text{eV} - 0.6\overline{6}\ \text{eV}\right)}{\left(11.5\times10^{14}\ \text{Hz} - 6.0\times10^{14}\ \text{Hz}\right)}\\ &= \frac{2.\overline{3}\ \text{eV}}{5.5\times10^{14}\ \text{Hz}}\\ &= 4.24\times10^{-15}\ \cancel{\text{eV}}\bullet\text{s}\times\left(\frac{1.60\times10^{-19}\ \text{J}}{1\ \cancel{\text{eV}}}\right)\\ &= 6.79\times10^{-34}\ \text{J}\bullet\text{s}\\ &= 6.8\times10^{-34}\ \text{J}\bullet\text{s}\end{aligned}$$

26. The flow chart says that the y-intercept should enable the calculation of the work function.

27. The y-intercept is a negative value that is not shown on the graph. An alternative approach is to use the x-intercept. This approach is based on the idea that when the maximum kinetic energy is zero, the frequency is the threshold frequency. This is shown by the following equation.

$$\begin{aligned}E_k &= hf - hf_o\\ 0 &= hf - hf_o\\ hf &= hf_o\\ f &= f_o\end{aligned}$$

When $E_k = 0$, the frequency is the threshold frequency.

This should make sense to you because in this case the incident photons supply just enough energy to free the electrons but no energy is left over to supply the electrons with kinetic energy. The threshold frequency can then be used to calculate the work function.

28. $x\text{-intercept} = f_o = 4.4\times10^{14}\ \text{Hz}$
work function $= W = ?$

$$\begin{aligned}W &= hf_o\\ &= \left(6.63\times10^{-34}\ \text{J}\bullet\text{s}\right)\left(4.4\times10^{14}\ \text{Hz}\right)\\ &= 2.917\times10^{-19}\ \text{J}\times\left(\frac{1\ \text{eV}}{1.60\times10^{-19}\ \text{J}}\right)\\ &= 1.8\ \text{eV}\end{aligned}$$

29. a.

Frequency of the incident photon
Maximum kinetic energy of ejected photoelectrons

Planck's constant → $\boxed{hf = E_{k_{max}} + W}$ ← Work function of the metal

b.

Planck's constant

Work function $\boxed{W = hf_o}$ Threshold frequency

c.

Charge of one electron

Maximum kinetic energy of ejected photoelectrons $\boxed{E_{k_{max}} = qV_{stop}}$ Stopping voltage

d.

Planck's constant

Speed of light

Energy of incident photon $\boxed{E = hf = \dfrac{hc}{\lambda}}$ Wavelength of incident photon

Frequency of incident photon

Planck's constant

30. Textbook question 3.a.:

$$\lambda_o = 310 \text{ nm}$$
$$= 310 \times 10^{-9} \text{ m}$$
$$= 3.10 \times 10^{-7} \text{ m}$$
$$f_o = ?$$

$$c = \lambda_o f_o$$
$$f_o = \frac{c}{\lambda_o}$$
$$= \frac{3.00 \times 10^{8} \text{ m/s}}{3.10 \times 10^{-7} \text{ m}}$$
$$= 9.677 \times 10^{14} \text{ Hz}$$
$$= 9.68 \times 10^{14} \text{ Hz}$$

Textbook question 3.b.:

$$f_o = 9.677 \times 10^{14} \text{ Hz}$$
$$W = ?$$

$$W = hf_o$$
$$= \left(6.63 \times 10^{-34} \text{ J} \bullet \text{s}\right)\left(9.677 \times 10^{14} \text{ Hz}\right)$$
$$= 6.416 \times 10^{-19} \text{ J}\left(\frac{1 \text{ eV}}{1.60 \times 10^{-19} \text{ J}}\right)$$
$$= 4.01 \text{ eV}$$

Textbook question 3.c.:

$$\lambda = 240 \text{ nm}$$
$$= 240 \times 10^{-9} \text{ m}$$
$$= 2.40 \times 10^{-7} \text{ m}$$
$$E_{k_{max}} = ?$$

$$hf = E_{k_{max}} + W$$
$$E_{k_{max}} = hf - W$$
$$= h\left(\frac{c}{\lambda}\right) - W$$
$$= \frac{\left(6.63 \times 10^{-34} \text{ J} \bullet \text{s}\right)\left(3.00 \times 10^{8} \text{ m/s}\right)}{\left(2.40 \times 10^{-7} \text{ m}\right)} - \left(6.416 \times 10^{-19} \text{ J}\right)$$
$$= 1.872 \times 10^{-19} \text{ J} \times \left(\frac{1 \text{ eV}}{1.60 \times 10^{-19} \text{ J}}\right)$$
$$= 1.17 \text{ eV}$$

Textbook question 4.a.:

$$W = 1.96 \text{ eV}\left(\frac{1.60 \times 10^{-19} \text{ J}}{1 \text{ eV}}\right)$$
$$= 3.136 \times 10^{-19} \text{ J}$$
$$= 3.14 \times 10^{-19} \text{ J}$$
$$\lambda_o = ?$$

$$W = hf_o$$
$$W = \frac{hc}{\lambda_o}$$
$$\lambda_o = \frac{hc}{W}$$
$$= \frac{\left(6.63 \times 10^{-34} \text{ J} \bullet \text{s}\right)\left(3.00 \times 10^{8} \text{ m/s}\right)}{3.136 \times 10^{-19} \text{ J}}$$
$$= 6.34 \times 10^{-7} \text{ m}$$

Textbook question 4.b.:

$$\lambda = 425 \text{ nm} = 4.25 \times 10^{-7} \text{ m}$$
$$E_{k_{max}} = ?$$

$$hf = E_{k_{max}} + W$$
$$E_{k_{max}} = hf - W$$
$$= \frac{hc}{\lambda} - W$$
$$= \frac{\left(6.63 \times 10^{-34} \text{ J} \bullet \text{s}\right)\left(3.00 \times 10^{8} \text{ m/s}\right)}{\left(4.25 \times 10^{-7} \text{ m}\right)} - \left(3.136 \times 10^{-19} \text{ J}\right)$$
$$= 1.544 \times 10^{-19} \text{ J}\left(\frac{1 \text{ eV}}{1.60 \times 10^{-19} \text{ J}}\right)$$
$$= 0.965 \text{ eV}$$

31. Textbook question 10.a.:

$$f_o = 6.7 \times 10^{14}\ \text{Hz}$$
$$\lambda = 350\ \text{nm}$$
$$= 350 \times 10^{-9}\ \text{m}$$
$$= 3.50 \times 10^{-7}\ \text{m}$$
$$E_{k_{max}} = ?$$

$$hf = E_{k_{max}} + W$$
$$E_{k_{max}} = hf - W$$
$$= \frac{hc}{\lambda} - hf_o$$
$$= h\left(\frac{c}{\lambda} - f_o\right)$$
$$= \left(6.63 \times 10^{-34}\ \text{J}\bullet\text{s}\right)\left(\frac{3.00 \times 10^{8}\ \text{m/s}}{3.50 \times 10^{-7}\ \text{m}} - 6.7 \times 10^{14}\ \text{Hz}\right)$$
$$= 1.2408 \times 10^{-19}\ \text{J}\left(\frac{1\ \text{eV}}{1.60 \times 10^{-19}\ \text{J}}\right)$$
$$= 0.775\ \text{eV}$$
$$= 0.78\ \text{eV}$$

Textbook question 11.a.:

$$W = 4.7\ \text{eV}\left(\frac{1.60 \times 10^{-19}\ \text{J}}{1\ \text{eV}}\right) = 7.52 \times 10^{-19}\ \text{J}$$
$$\lambda_o = ?$$

$$W = hf_o$$
$$W = \frac{hc}{\lambda_o}$$
$$\lambda_o = \frac{hc}{W}$$
$$= \frac{\left(6.63 \times 10^{-34}\ \text{J}\bullet\text{s}\right)\left(3.00 \times 10^{8}\ \text{m/s}\right)}{7.52 \times 10^{-19}\ \text{J}}$$
$$= 2.6449 \times 10^{-7}\ \text{m}$$
$$= 2.6 \times 10^{-7}\ \text{m}$$

32. $\lambda = 455\ \text{nm}$

$$= 4.55 \times 10^{-7}\ \text{m}$$
$$W = 2.49\ \text{eV}\left(\frac{1.60 \times 10^{-19}\ \text{J}}{1\ \text{eV}}\right)$$
$$= 3.984 \times 10^{-19}\ \text{J}$$
$$= 3.98 \times 10^{-19}\ \text{J}$$
$$v_{max} = ?$$
$$m = 9.11 \times 10^{-31}\ \text{kg}$$

Step 1: Find the maximum kinetic energy.

$$hf = E_{k_{max}} + W$$
$$E_{k_{max}} = hf - W$$
$$= \frac{hc}{\lambda} - W$$
$$= \frac{\left(6.63 \times 10^{-34}\ \text{J}\bullet\text{s}\right)\left(3.00 \times 10^{8}\ \text{m/s}\right)}{4.55 \times 10^{-7}\ \text{m}} - \left(3.984 \times 10^{-19}\ \text{J}\right)$$
$$= 3.874 \times 10^{-20}\ \text{J}$$
$$= 3.87 \times 10^{-20}\ \text{J}$$

Step 2: Calculate the maximum speed from the maximum kinetic energy.

$$
\begin{aligned}
E_k &= \frac{1}{2}mv^2 \\
E_{k_{\max}} &= \frac{1}{2}m(v_{max})^2 \\
v_{max} &= \sqrt{\frac{2E_{k_{max}}}{m}} \\
&= \sqrt{\frac{2(3.874\times10^{-20}\ \text{J})}{9.11\times10^{-31}\ \text{kg}}} \\
&= 2.916\times10^{5}\ \text{m/s} \\
&= 2.92\times10^{5}\ \text{m/s}
\end{aligned}
$$

33. $\lambda = 250\ \text{nm}$

$= 2.50\times10^{-7}\ \text{m}$

$$
\begin{aligned}
E_{k_{max}} &= 1.10\ \text{eV}\left(\frac{1.60\times10^{-19}\ \text{J}}{1\ \text{eV}}\right) \\
&= 1.76\times10^{-19}\ \text{J}
\end{aligned}
$$

$W = ?$

$$
\begin{aligned}
hf &= E_{k_{max}} + W \\
W &= hf - E_{k_{max}} \\
&= \frac{hc}{\lambda} - E_{k_{max}} \\
&= \frac{(6.63\times10^{-34}\ \text{J}\bullet\text{s})(3.00\times10^{8}\ \text{m/s})}{2.50\times10^{-7}\ \text{m}} - 1.76\times10^{-19}\ \text{J} \\
&= 6.196\times10^{-19}\ \text{J} \\
&= 6.20\times10^{-19}\ \text{J}
\end{aligned}
$$

Section 2: Activity 2

1. The semiconductor diode uses less power, is smaller, gives off much less heat, is less fragile, and is much cheaper to mass produce.

2. Although the results may vary, it is reasonable to expect a current of between 3 mA and 6 mA for a low-voltage setting.

3. The ammeter displays a zero current when the LED is reversed from the light-emitting position.

4. A diode is a device that allows current to pass in only one direction. The answers to the previous two questions indicate that conventional current can only flow in one direction and when it does flow, light is emitted.

5. The arrow in the symbol for the LED reminds the person reading the schematic diagram that conventional current can flow only in the direction indicated by the arrow. The symbol also indicates a photon to remind the user that this is a light-emitting device.

6. As the current increases, more charges flow through the LED. There is a one-to-one correspondence between the number of charges that pass through the circuit and the number of photons that are emitted. This means that as current increases, more charges flow and more photons are released, making the light from the LED look brighter.

7. You verified the following properties:

   - LEDs will only pass a current in one direction.
   - LEDs emit light only within a narrow band of wavelengths.

8. $E = \frac{hc}{\lambda}$

   $h = \frac{E\lambda}{c}$

   From the rearrangement of the equation, it can be see that wavelength (λ) and energy (E) need to be measured. The speed of light does not need to be measured because it is a constant.

9.

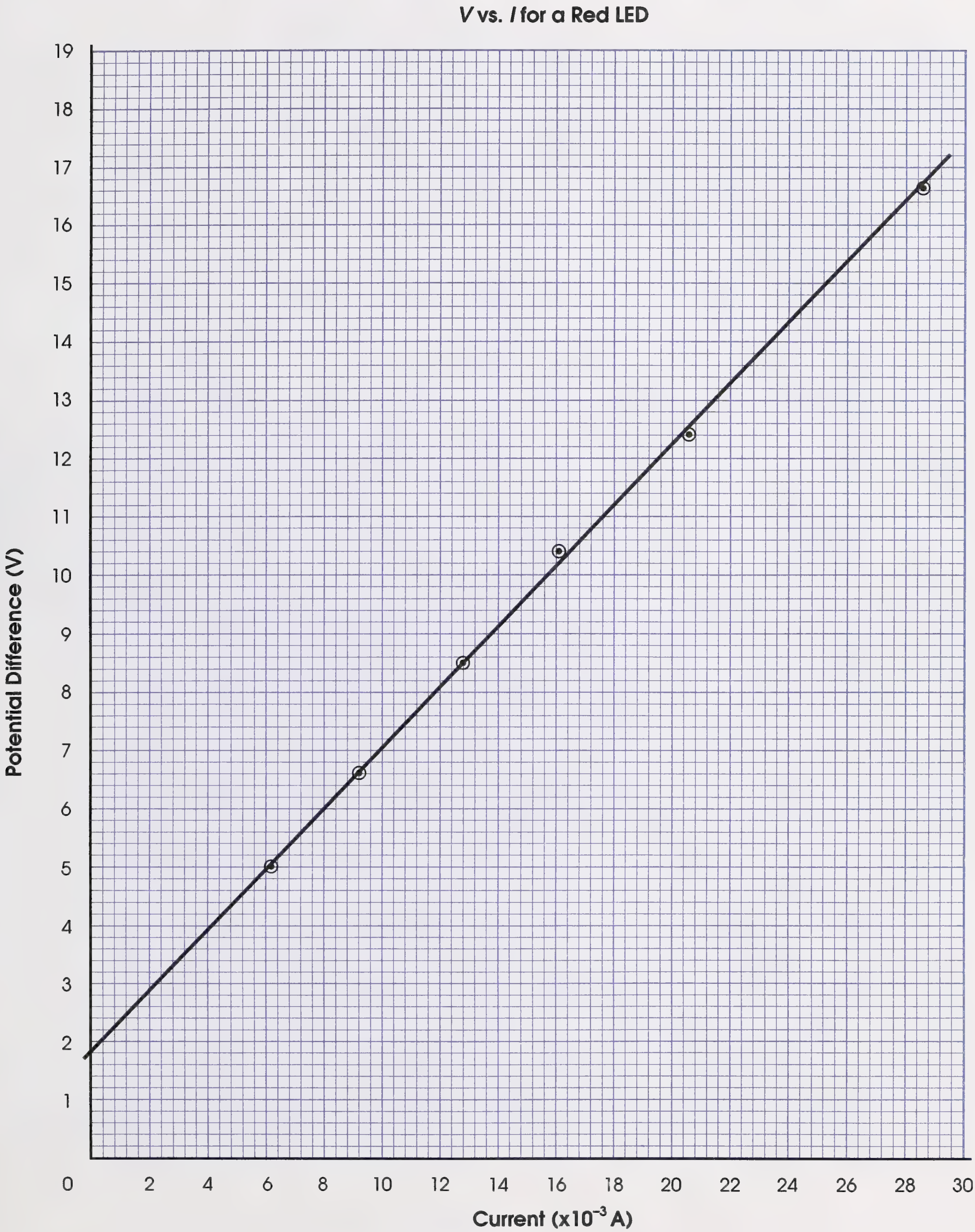
Red LED $\lambda = 6.3 \times 10^{-7}$ m	
V (Volts)	I $(\times 10^{-3}$ A$)$
5.02	6.20
6.62	9.21
8.52	12.80
10.39	16.31
12.44	20.5
16.62	28.6

10.

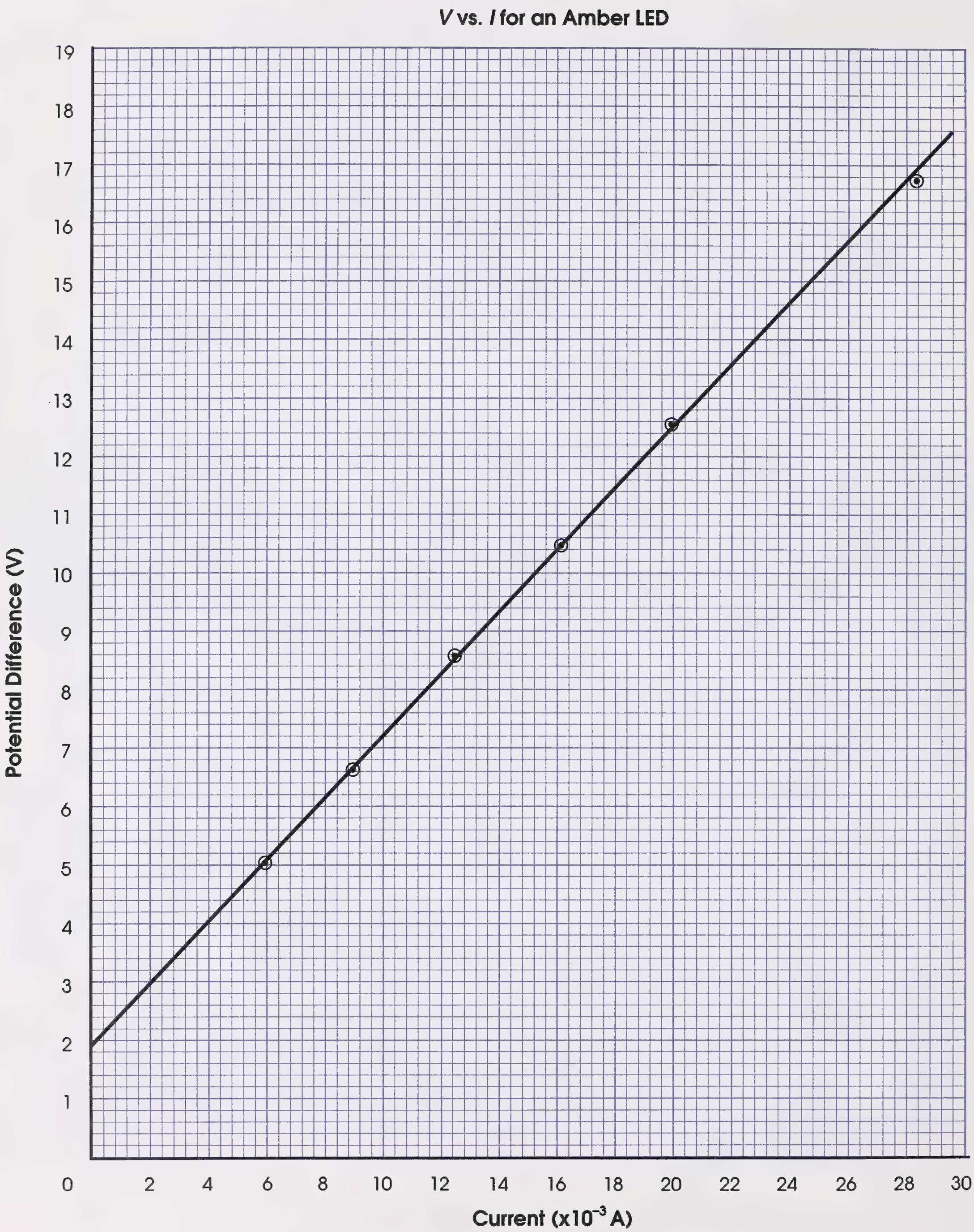
Amber LED $\lambda = 5.9 \times 10^{-7}$ m	
V (Volts)	I $(\times 10^{-3}$ A$)$
5.10	6.04
6.69	9.01
8.60	12.55
10.48	16.07
12.55	19.99
16.79	28.3

Green LED $\lambda = 5.4 \times 10^{-7}$ m	
V (Volts)	I $(\times 10^{-3}$ A$)$
5.08	5.85
6.69	8.81
8.60	12.4
10.49	16.0
12.53	19.9
16.79	27.9

11.

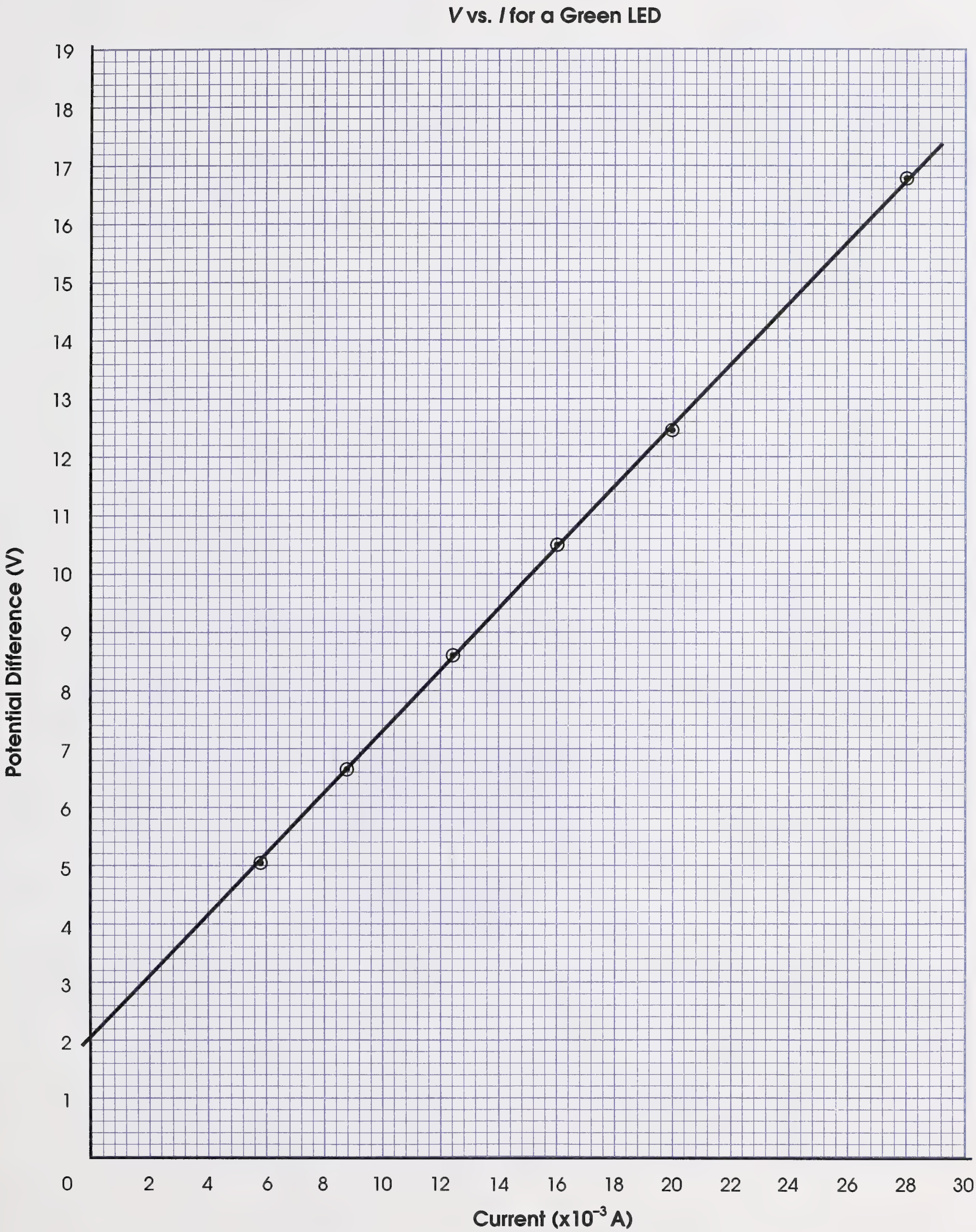

V vs. I for a Red LED
Potential Difference (V)
Current (x10^{-3} A)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30

12.



V vs. I for an Amber LED
Potential Difference (V)
Current (x10^{-3} A)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19

13.


V vs. *I* for a Green LED
Potential Difference (V)
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Current ($\times 10^{-3}$ A)

14. The following results represent typical values for a LED in series with a 510-Ω resistor. Your results may vary slightly.

Red LED:

$$\begin{aligned}\text{slope} &= \frac{\text{rise}}{\text{run}}\\ &= \frac{17.0\ \text{V} - 3.0\ \text{V}}{29.2\times10^{-3}\ \text{A} - 2.3\times10^{-3}\ \text{A}}\\ &= 520\ \text{V/A}\\ &= 5.2\times10^{2}\ \Omega\end{aligned}$$

The y-intercept for this graph is 1.85 V.

Amber LED:

$$\begin{aligned}\text{slope} &= \frac{\text{rise}}{\text{run}}\\ &= \frac{17.6\ \text{V} - 3.0\ \text{V}}{29.6\times10^{-3}\ \text{A} - 2.0\times10^{-3}\ \text{A}}\\ &= 529\ \text{V/A}\\ &= 5.3\times10^{2}\ \Omega\end{aligned}$$

The y-intercept for this graph is 1.95 V.

Green LED:

$$\begin{aligned}\text{slope} &= \frac{\text{rise}}{\text{run}}\\ &= \frac{17.0\ \text{V} - 5.0\ \text{V}}{28.4\times10^{-3}\ \text{A} - 5.6\times10^{-3}\ \text{A}}\\ &= 526\ \text{V/A}\\ &= 5.3\times10^{2}\ \Omega\end{aligned}$$

The y-intercept for the graph is 2.1 V.

The slopes represent the equivalent resistance of each LED in series with the 510-Ω resistor.

15. As the following flow chart indicates, the y-intercept represents the value $\frac{hc}{q\lambda}$.

$$V_{power\ supply} = RI + \underbrace{\frac{hc}{q\lambda}}$$

By inspection:

$$y = mx + b$$

16. These answers are consistent with the sample data used for earlier answers within the investigation. Your answers may differ slightly.

Red LED

$b = 1.85\ \text{V}$

$\lambda = 6.3\times10^{-7}\ \text{m}$

$$\begin{aligned}h &= \frac{q\lambda b}{c}\\ &= \frac{\left(1.60\times10^{-19}\ \text{C}\right)\left(6.3\times10^{-7}\ \text{m}\right)(1.85\ \text{V})}{\left(3.00\times10^{8}\ \text{m/s}\right)}\\ &= 6.216\times10^{-34}\ \text{J}\bullet\text{s}\\ &= 6.2\times10^{-34}\ \text{J}\bullet\text{s}\end{aligned}$$

Amber LED

$b = 1.95\ \text{V}$

$\lambda = 5.9 \times 10^{-7}\ \text{m}$

$$h = \frac{q\lambda b}{c}$$
$$= \frac{\left(1.60 \times 10^{-19}\ \text{C}\right)\left(5.9 \times 10^{-7}\ \text{m}\right)\left(1.95\ \text{V}\right)}{\left(3.00 \times 10^{8}\ \text{m/s}\right)}$$
$$= 6.136 \times 10^{-34}\ \text{J} \bullet \text{s}$$
$$= 6.1 \times 10^{-34}\ \text{J} \bullet \text{s}$$

Green LED

$b = 2.1\ \text{V}$

$\lambda = 5.4 \times 10^{-7}\ \text{m}$

$$h = \frac{q\lambda b}{c}$$
$$= \frac{\left(1.60 \times 10^{-19}\ \text{C}\right)\left(5.4 \times 10^{-7}\ \text{m}\right)\left(2.1\ \text{V}\right)}{\left(3.00 \times 10^{8}\ \text{m/s}\right)}$$
$$= 6.048 \times 10^{-34}\ \text{J} \bullet \text{s}$$
$$= 6.0 \times 10^{-34}\ \text{J} \bullet \text{s}$$

17. • Determine the average value of Planck's constant.

$$h_{ave} = \frac{\sum h}{n}$$
$$= \frac{\left(6.2 \times 10^{-34}\ \text{J} \bullet \text{s} + 6.1 \times 10^{-34}\ \text{J} \bullet \text{s} + 6.0 \times 10^{-34}\ \text{J} \bullet \text{s}\right)}{3}$$
$$= 6.1 \times 10^{-34}\ \text{J} \bullet \text{s}$$

• Calculate the percent error.

$$\text{percent error} = \frac{\left|\text{theoretical value} - \text{experimental value}\right|}{\text{theoretical value}} \times 100\%$$
$$= \frac{\left|6.63 \times 10^{-34}\ \text{J} \bullet \text{s} - 6.1 \times 10^{-34}\ \text{J} \bullet \text{s}\right|}{6.63 \times 10^{-34}\ \text{J} \bullet \text{s}} \times 100\%$$
$$= 8.0\%$$

18. The answer to this question reflects the sample data that was presented earlier. You may evaluate the experiment differently if you had different results.

    The percent error is less than 10%, which is acceptable for this type of experiment that can only produce data accurate to two significant digits. However, the fact that all the values of Planck's constant are so close to each other implies that there is systematic error influencing all of this data. The likely cause of this error is a simplification made in the derivation of the equation $V = RI + \frac{hc}{q\lambda}$. This equation does not include an extra term that adjusts for an energy transition within the LED. You'll learn more about this when you study the band theory of solids in Module 9.

19. Photocells can be used to automatically turn lights on at sunset and to turn them off after sunrise. This is used in streetlights to ensure that the lights are only used when they are needed so that energy can be saved.

20. A photovoltaic cell that operates on the photoelectric effect can open and close doors automatically when something breaks the light beam. This means that people who are unable to grab handles or pull open heavy doors now have access to the building.

21. Many calculators that are solar-powered use photovoltaic cells to convert the energy in photons into a tiny electric current. This photoelectric current is sufficient to operate the calculator.

22. a. Light photons → Photo receptors in the eye convert the light energy into a weak electric current. → The weak electric current carries a signal to the part of the brain responsible for vision.

    b. The photoreceptors in your eyes are sensitive to photons from the visible part of the spectrum. Ultraviolet photons have a higher frequency and therefore a higher energy content that is sufficient to do permanent damage to the photoreceptors in the eye.

23. a. $\lambda = 665 \text{ nm} = 6.65 \times 10^{-7} \text{ m}$

    $E = ?$

$$E = \frac{hc}{\lambda}$$

$$= \frac{(6.63 \times 10^{-34} \text{ J} \bullet \text{s})(3.00 \times 10^{8} \text{ m/s})}{(6.65 \times 10^{-7} \text{ m})}$$

$$= 2.991 \times 10^{-19} \text{ J}$$

This is the energy from one photon. Since it takes nine photons to convert one carbon dioxide molecule, the total energy is nine times this value.

$$E = 9(2.991 \times 10^{-19} \text{ J})$$

$$= 2.692 \times 10^{-18} \text{ J}$$

$$= 2.69 \times 10^{-18} \text{ J}$$

b. In this equation six carbon dioxide molecules are converted. This means that 54 red light photons would be needed. The total energy is therefore 54 times the energy of one light photon.

$$\begin{aligned} E &= 54\left(2.991\times10^{-19}\ \text{J}\right) \\ &= 1.615\times10^{-17}\ \text{J} \\ &= 1.62\times10^{-17}\ \text{J} \end{aligned}$$

c. Since the chlorophyll molecules look green, they reflect green light. It follows that they must be absorbing light from the red and blue ends of the spectrum.

d. If the energy of photons from the visible spectrum provides just the right amount of energy, infrared photons would not be able to transfer enough energy to make these reactions happen. This is due to the low frequency of infrared radiation. On the other hand, ultraviolet photons have too much energy and could damage the cells by leaving key molecules ionized instead of energized.

24.

$$\begin{aligned} \sum E_{in} &= \sum E_{out} \\ E_{power\ supply} &= E_{x\text{-}ray\ photons} \\ Vq &= hf_{max} \end{aligned}$$

25. As the current is increased within the x-ray tube, there are more electrons available to collide with the metal reflector. Each of these electrons could then create additional x-rays.

26. As the voltage in the tube is increased, more energy is made available to each of the electrons. These electrons can then make more energy available to each of the x-ray photons. If the x-ray photons have more energy, they will have a correspondingly higher frequency. This idea is summarized in the answer to question 24.

27. $V = 7.0\times10^{3}\ \text{V}$

$f_{max} = ?$

$$\begin{aligned} \sum E_{in} &= \sum E_{out} \\ E_{power\ supply} &= E_{x\text{-}ray\ photons} \\ Vq &= hf_{max} \\ f_{max} &= \frac{Vq}{h} \\ &= \frac{\left(7.0\times10^{3}\ \text{V}\right)\left(1.60\times10^{-19}\ \text{C}\right)}{6.63\times10^{-34}\ \text{J}\bullet\text{s}} \\ &= 1.689\times10^{18}\ \text{Hz} \\ &= 1.7\times10^{18}\ \text{Hz} \end{aligned}$$

28. a. $V = 1.95 \times 10^4\ \text{V}$

$\lambda_{min} = ?$

$$\sum E_{in} = \sum E_{out}$$

$$E_{power\ supply} = E_{x\text{-}ray\ photons}$$

$$Vq = \frac{hc}{\lambda_{min}}$$

$$\lambda_{min} = \frac{hc}{Vq}$$

$$= \frac{\left(6.63 \times 10^{-34}\ \text{J}\bullet\text{s}\right)\left(3.00 \times 10^{8}\ \text{m/s}\right)}{\left(1.95 \times 10^{4}\ \text{V}\right)\left(1.60 \times 10^{-19}\ \text{C}\right)}$$

$$= 6.375 \times 10^{-11}\ \text{m}$$

$$= 6.38 \times 10^{-11}\ \text{m}$$

b. If the technician is performing a test while the television is operating, there is a possibility of being exposed to x-rays. Many televisions have the parts that produce the x-rays shielded in a metal case with a warning explaining that if the case is removed, dangerous exposure to x-rays is possible.

29. $\lambda_{min} = 7.5 \times 10^{-10}\ \text{m}$

$V = ?$

$$\sum E_{in} = \sum E_{out}$$

$$E_{power\ supply} = E_{x\text{-}ray\ photons}$$

$$Vq = \frac{hc}{\lambda_{min}}$$

$$V = \frac{hc}{q\lambda_{min}}$$

$$= \frac{\left(6.63 \times 10^{-34}\ \text{J}\bullet\text{s}\right)\left(3.00 \times 10^{8}\ \text{m/s}\right)}{\left(1.60 \times 10^{-19}\ \text{C}\right)\left(7.5 \times 10^{-10}\ \text{m}\right)}$$

$$= 1.6575 \times 10^{3}\ \text{V}$$

$$= 1.7 \times 10^{3}\ \text{V}$$

Section 2: Activity 3

1. The following derivation is valid for photons only.

$$p = \frac{E}{c} = \frac{hf}{c}$$

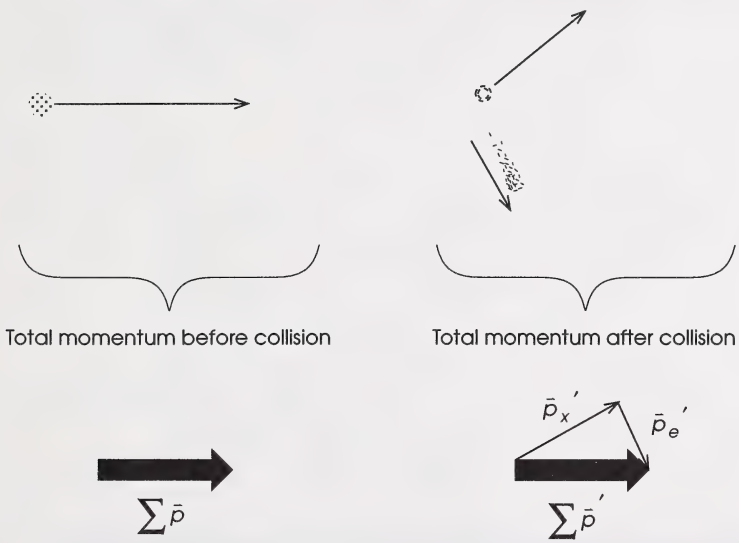
2. The following derivation is valid for photons only.

$$p = \frac{E}{c} = \frac{hf}{c} = \frac{h\left(\frac{\cancel{c}}{\lambda}\right)}{\cancel{c}} = \frac{h}{\lambda}$$

3. The photons with the greatest momentum would have a high frequency or a small wavelength. This means that x-ray photons and gamma ray photons would have the greatest momentum values.

4. a. This is the initial x-ray photon moving into the chamber.
   b. This is a detector set up to detect and measure the energy of scattered x-ray photons.
   c. This is a scattered x-ray photon moving away after the initial x-ray photon collided with an electron.
   d. This is the track of an electron that the initial x-ray collided with.

5.



6. a. This is the source of photons.

   b. This is a single photon travelling towards the slits.

   c. This is a bright region on the photographic paper which has been bombarded by a large number of photons.

   d. This is the photograph paper that records the landing position of the photons.

7. In Taylor's experiment only one photon approached the slits at a time, so the pattern took months to develop.

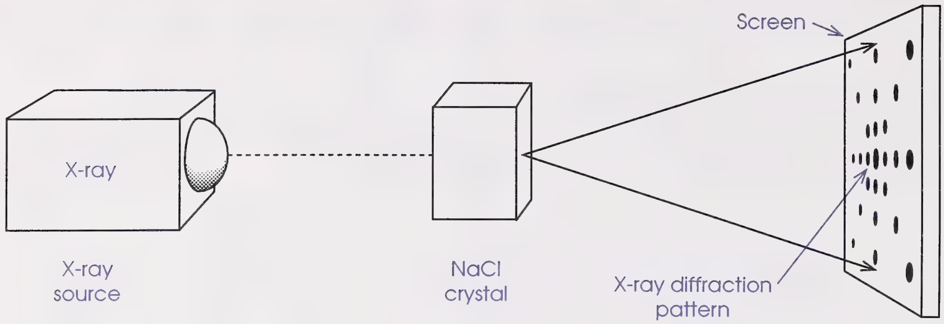
8. The wave model is needed to predict the pattern of bright and dark bands created by the photons.

9. Radio waves are more wave-like and gamma-ray photons are more particle-like.

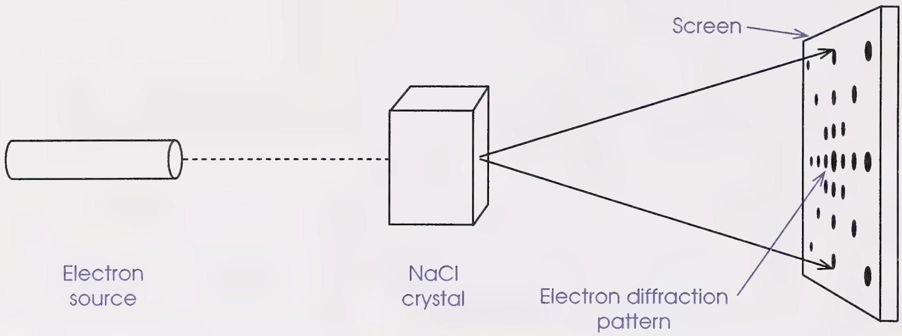
10. The bright lines are regions that have a high probability that a single photon will land in these areas.

11. A wave will not diffract around an obstacle if the wavelength is much smaller than the size of the obstacle.

12.



13.



14.

	X-ray Photons	Electrons
Speed	Photons can only travel at the speed of light. If they stop, they are annihilated.	Electrons can travel at any speed lower than the speed of light.
Rest Mass	Since photons cannot be at rest, they do not have a rest mass.	Electrons have a rest mass of 9.11×10^{-31} kg.

15. Textbook question 9:

$\lambda = 4.00\times10^{2}\ \text{nm} = 4.00\times10^{-7}\ \text{m}$

$p = ?$

$$p = \frac{h}{\lambda}$$

$$= \frac{6.63\times10^{-34}\ \text{J}\bullet\text{s}}{4.00\times10^{-7}\ \text{m}}$$

$$= 1.66\times10^{-27}\ \text{kg}\bullet\text{m/s}$$

Textbook question 10:

$\lambda = 7.00 \times 10^{2}\ \text{nm} = 7.00 \times 10^{-7}\ \text{m}$
$p = ?$

$$p = \frac{h}{\lambda}$$
$$= \frac{6.63 \times 10^{-34}\ \text{J} \bullet \text{s}}{7.00 \times 10^{-7}\ \text{m}}$$
$$= 9.47 \times 10^{-28}\ \text{kg} \bullet \text{m/s}$$

Textbook question 11:

$m = 9.11 \times 10^{-31}\ \text{kg}$
$v = 3.0 \times 10^{6}\ \text{m/s}$
$\lambda = ?$

$$\lambda = \frac{h}{mv}$$
$$= \frac{6.63 \times 10^{-34}\ \text{J} \bullet \text{s}}{\left(9.11 \times 10^{-31}\ \text{kg}\right)\left(3.0 \times 10^{6}\ \text{m/s}\right)}$$
$$= 2.43 \times 10^{-10}\ \text{m}$$
$$= 2.4 \times 10^{-10}\ \text{m}$$

Textbook question 12:

$\lambda = 3.0 \times 10^{-10}\ \text{m}$
$m = 9.11 \times 10^{-31}\ \text{kg}$
$v = ?$

$$\lambda = \frac{h}{mv}$$
$$v = \frac{h}{m\lambda}$$
$$= \frac{6.63 \times 10^{-34}\ \text{J} \bullet \text{s}}{\left(9.11 \times 10^{-31}\ \text{kg}\right)\left(3.0 \times 10^{-10}\ \text{m}\right)}$$
$$= 2.4 \times 10^{6}\ \text{m/s}$$

16. Textbook question 2.1:

To increase the wavelength of the electrons, the velocity should be smaller, which implies that the energy should be reduced. This is verified by the equation $\lambda = \frac{h}{mv}$.

Textbook question 2.2:

Photons cannot be slowed down because they travel only at one speed. The only way to increase the wavelength of a photon is to decrease its frequency, which is equivalent to decreasing its energy. This is summarized by the equation $E = hf = \frac{hc}{\lambda}$. The process of reducing the energy of a photon could be accomplished by scattering the photon off an electron, as demonstrated by the Compton effect.

Textbook question 2.3:

The beam of light will diffract as it passes through the hole, making the direction of the beam difficult to determine.

Section 2: Follow-up Activities

Extra Help

How the Photon Model and Wave-Particle Duality Developed		
Name of Experiment or Apparatus	**How did this work advance the photon model of light or wave-particle duality?**	**New Equations that Developed from this Work**
Blackbody Radiation	Max Planck proposed that light energy is quantized.	$E = hf = \frac{hc}{\lambda}$
Photoelectric Effect	Einstein expands on Planck's work to establish the photon model of light. Individual photons can interact to liberate individual electrons from these atoms.	$hf = E_{k_{max}} + W$ $W = hf_o$ $E_{k_{max}} = qV_{stop}$
Compton Effect	Compton verified Einstein's prediction that photons also have momentum that allows them to behave in collisions as particles do. This leads to the notion of wave-particle duality.	$\underbrace{p = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda}}_{\text{photons only}}$
Electron Diffraction	De Broglie showed that the wave particle duality can be applied to electrons. Electrons have a wavelength and observable wave properties.	$\underbrace{\lambda = \frac{h}{mv}}_{\text{wavelength of particles}}$

Enrichment

1. a. Diodes from combinations of gallium and aluminum with arsenic and phosphorus can emit light when they are properly connected to a circuit.

   b. In a laser, diode crystals are made so that the light that is produced reflects back and forth within the crystal. Finally, the light is allowed to escape as a beam of coherent, monochromatic light.

   c. A reverse biased pn-junction can be used to detect light in devices like CD players and in supermarket barcode scanners.

2. The possible applications of the scanning tunnelling microscope are numerous in the area of manipulating atoms. Atoms could be moved into arrangements that could produce high-density storage for computer chips. Atoms could also be moved into positions necessary for custom molecules that could be used in the pharmaceutical industry.

NOTES

NOTES

Physics 30

Student Module Booklet
Module 7

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